(Re)assembling air quality science: Exploring air quality knowledge production

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Abstract

In this thesis I critically examine the production of knowledge about air quality. I do so to explore how air quality knowledge is produced, and critically engage with how we can reconfigure our relations with the air to begin to address air inequalities. I draw upon my direct involvement in three different forms of doing air quality science. I analyse these involvements across three papers that make up the thesis along with Introduction, Literature Review, Methodology, and Conclusion chapters.

In Paper 1, using an autoethnographic analysis of PhD fieldwork, I contrast the difference between ‘ready made science’ and ‘science in the making’ through challenging my own conventional account of a school air quality monitoring project. In Paper 2, I show how a research-business project in UK schools that measured indoor air quality to assess the effectiveness of an air cleaning device became re-assembled following the emergence of COVID-19. In Paper 3, I reflect on a citizen science air quality monitoring project: drawing on interviews with citizen scientists I illuminate tensions in the dynamics of knowledge production, including air quality research design and reporting. Moreover, drawing upon science and technology studies, critical physical geography, and environmental justice literatures, I propose a new Critical Air Quality Science framework.

This thesis contributes to ‘hybrid’ ways of thinking about the air that pays attention to its materiality, but also its cultural, social, economic, and political relations: in particular for indoor air quality. Additionally, through drawing upon Actor-Network Theory and other ‘more-than-human’ approaches, I contribute to research characterising the mediating role of scientists in the production of the air. Moreover, through focusing on my own mediating role in the doing of air quality science, I contribute to emerging strands of environmental justice, namely epistemic justice.

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List of Abbreviations

AAP – Ambient Air Pollution

AAQ – Ambient Air Quality

AC/H – Air Change Rate

ANT – Actor-Network Theory

AQEG – Air Quality Expert Group

ASHRAE – The American Society of Heating, Refrigerating and Air-Conditioning Engineers

AURN – Automatic Urban and Rural Network

BB101 – Building Bulletin 101

BOS – Better Old Swan

CAQS – Critical Air Quality Science

CBPR – Community Based Participatory Research

COVD-19 – Coronavirus 2019

CO_2 – Carbon Dioxide

CEN – The European Committee for Standardization

CPC – Condensation Particle Counter

CPG – Critical Physical Geography

CS – Citizen Science

DfE – UK Department for Education

DMA – Differential Mobility Analyser

EF – Extended Facts

EJ – Environmental Justice

EPC – Extended Peer Community

HEPA – High Efficiency Particulate Air

IAQ – Indoor Air Quality

I/O – Indoor/Outdoor

IPA – Isopropyl Alcohol

LTN – Low Traffic Neighbourhood

NAQTS – National Air Quality Testing Services Ltd.

NEU – National Education Union

NIHR CLAHRC-NWC – National Institute for Health Research Collaboration for Leadership in Applied Health Research and Care in the North West Coast area of England

NO_2 – Nitrogen Dioxide

NRP – Neighbourhood Resilience Programme

OPP – Obligatory Passage Point

PEMS – Portable Emissions Measurement System

PM – Particulate Matter

$PM_{2.5}$ – Particulate Matter that has a diameter of less than 2.5 microns

PM_{10} – Particulate Matter that has a diameter of less than 10 microns

PN – Particle Number

PNC – Particle Number Concentration

PNS – Postnormal Science

RMS – Ready Made Science

SAGE-EMG – Scientific Advisory Group for Emergencies-Environment and Modelling Group

SSK – Sociology of Scientific Knowledge

STS – Science and Technology Studies

UFPs – Ultrafine Particles

VOCs – Volatile Organic Compounds

V2000 – NAQTS V2000

WHO – World Health Organization

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The thing that I have learned more than anything is that one cannot do a PhD alone. I have so many people to thank. Here goes…

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Author's Declaration

This thesis is my own work and has not been submitted for the award of a higher degree elsewhere. This thesis contains three papers that have either been published, are in press, or are in preparation for submission. They are listed below with a brief description of the contribution that my co-authors and I made. The word count of this thesis is ~61,000 words, and it does not exceed the permitted maximum.

1. **Booker, D.,** From (Particulate) Matter to Form: Opening the black box of doing PhD air quality science. *To be submitted*.

2. **Booker, D**., Walker, G., &. Young, P.J. Unstable air: How COVID-19 remade knowing air quality in school classrooms. *Ephemera: Theory & Politics in Organization (in press).* **CRediT authorship contribution statement – Douglas Booker**: Conceptualisation, Data curation, Formal Analysis, Funding acquisition, Investigation, Project administration, Resources, Validation, Visualisation, Writing – original draft, Writing – review & editing. **Gordon Walker**: Writing – review & editing. **Paul J. Young**: Writing – review & editing.

3. **Booker, D**., Walker, G., Young, P., & Porroche-Escudero, A. (2023). A Critical Air Quality Science Perspective on Citizen Science in Action. *Local Environment*, *28*(1), 31–46. https://doi.org/10.1080/13549839.2022.2118700. **CRediT authorship contribution statement – Douglas Booker**: Conceptualisation, Data curation, Formal Analysis, Funding acquisition, Investigation, Project administration, Resources, Validation, Visualisation, Writing – original draft, Writing – review & editing. **Gordon Walker**: Writing – review & editing. **Paul J. Young**: Writing – review & editing. **Ana Porroche-Escudero:** Funding acquisition, Writing – review & editing.

1. Introduction

> *"Air pollution is a thoroughly hybrid phenomenon. It is composed of inseparable physical, scientific, cultural, social, economic and political dimensions. It shows up on the scientific instruments of atmospheric scientists and in the persistent cough of an urban dweller. It appears on the pages of scientific journals and in conversations between parents in school playgrounds. Like many contemporary environmental problems, which are of concern to both scientists and ordinary people, it transgresses boundaries of nature and culture. It requires therefore broad, diverse and heterogeneous kinds of thinking"* (Cupples, 2009: 207).

Cupples's description of the air as a "hybrid" phenomenon that is known and produced in a variety of ways is part of the argument she makes for *new ways* of doing air quality science. She outlines the air as something that is both *formally* known by scientists using their air quality monitors and computer models, but also *informally* known by city dwellers who develop breathing difficulties, as well as by the parents of kids at a school near a busy road who can feel the air quality worsening during pick up and drop off times. Here the air's multi-faceted production is made clear: notwithstanding its production through material atmospheric reactions, it is both the product of emissions from polluting sources such as vehicles, but also social practices and temporal structures that legislate for many vehicles arriving in a single place at the same time. I begin with this quote because it introduces a view of the air that I deploy across this thesis, as I draw on the air's material, social, cultural, economic, and political relations to understand how knowledge of it is – and should be – produced. In this chapter, I provide some context for the work that is to follow, including the background, aims, contributions, research questions, and the structure of the thesis.

1.1. Background

The air is a hybrid phenomenon. Yet its study, either as air *quality* or air *pollution*, is often siloed along a nature / culture divide: its materiality (or nature) is studied by natural scientists and its social elements (or culture) remain the domain of social scientists. Despite these two sides dealing with the same problem, they are engaging with different, or indeed multiple airs. The air has primarily been made visible and governed through the efforts of natural science,[1] which comes from a particular ontological and epistemological viewpoint that views an air 'out there' to be discovered, quantified, and ordered by the activities of science. From measurement to modelling, air quality science has contributed to established understandings that air pollution affects every organ in the body increasing the risk of various diseases across a human's lifespan (RCP, 2016), reducing life expectancy and resulting in premature deaths (Dockery et al., 1993). These understandings have permitted estimates of the human toll from air pollution. For example, based on the Global Burden of Disease project (HEI, 2019), the World Health Organization (WHO) reports that annually around 7 million premature deaths are linked to air pollution exposure, making it the "leading environmental risk factor globally" (WHO, 2021).

These measurement and modelling activities have also contributed to understandings that the air's negative effects are felt unequally, proving central to claims of environmental injustice. There has been a multitude of research that has shown that the distribution of air pollution can be worse for certain communities (often based around socioeconomic status, and race) on a range of geographical scales, including on a global (e.g. Apte et al., 2021), country (e.g. Mitchell and Dorling, 2003; Boing et al., 2022), and city basis (e.g. Namdeo and Stringer, 2008; Ferguson et al., 2021). At the same time, air quality science has gathered and provided evidence to show how these disproportionate exposures can be inversely related to the production of air pollution. That is, those living in more polluted areas tend to emit less air pollution than those who live in less polluted areas (e.g. Barnes, Chatterton, and Longhurst, 2019). In other words, the pollut*ed* – rather than the pollut*er* – is paying the price of air pollution.

[1] Natural science on air quality comes from a range of disciplines including atmospheric chemistry and physics. While few use the term "air quality science" as an academic discipline per se, I use this term across this thesis to bundle these natural science activities under a single label.

We have never known the air and its – disproportionate – effects better in scientific terms, yet it remains a pervasive and complex problem. This is not to say that the air quality has not measurably improved in many cases. However, relative disparities still exist (Colmer et al., 2020), and the rate at which we learn of its harms appears to be outpacing our efforts to improve it. Moreover, the rate at which the air is improving may well not be equally felt. One UK based study showed that the greatest improvements tend to be found in the least deprived areas, with slower improvements in the most deprived areas (Mitchell et al., 2015).

The goal of air quality science has been to provide evidence to "reduce air pollution by encouraging people to act" (Cupples, 2009: 209), whether that be through bottom-up behaviour change initiatives, such as encouraging walking to school on less polluted routes (e.g. Varaden et al., 2021), or top-down public policies, such as ultra-low emission zones (e.g. Ma et al., 2021). Indeed, air quality science has been – and remains – essential in efforts to reduce air pollution exposure and improve air quality, in part because the air's perception is wrapped up in the technical infrastructures that observe it. For example, in the UK the Automatic Urban and Rural Network (AURN), a system of sophisticated air quality monitors reporting on a variety of different air pollutants in near real-time, has, in combination with other tools and datasets, allowed scientists to estimate the number of premature deaths associated with air pollution in the UK to be between 28,000 and 36,000 per year (COMEAP, 2009). These technical infrastructures are proliferating, facilitating our relation to a growing list of the air's material constituents at an ever-increasing spatiotemporal resolution. This includes through developments in 'low-cost' sensors (e.g. Kumar et al., 2015; Peters et al., 2022), mobile air quality measurements (e.g. Apte et al., 2017; Padilla et al., 2022; Amos et al., 2022), and air quality monitors that can measure emerging pollutants of concern at a non-exorbitant cost (e.g. Booker, 2018).

Notwithstanding these innovations, the question of what constitutes poor air quality, how it presents itself, and how it can be identified remains unresolved. This is because air quality is neither a fixed material reality nor a static body of knowledge: what is considered to be safe or harmful, 'fresh' or 'polluted', is a fluid and evolving cultural construct that undergoes changes over time (Douglas, 1966). Indeed, what comes to count as air *pollution*, or indeed air *quality,* changes as our capability to measure the air develops, new material constituents are identified, and new sources emerge. As such, air quality science does “not simply reflect pollution ‘out there’ but contribute[s] to a situated and partial understanding of it” (Garnett, 2018).

As Kenis and Loopmans (2022: 565) argue, “while we need processes of scientific translation to understand the chemical composition and spatiotemporal dynamics of air, science cannot be the only form of knowledge mobilised.” Indeed, as well as being “a mass of abstractly estimated deaths” air pollution can also be made visible and known through “curtailing the life of a real and differentially vulnerable individual” (Walker, Booker, & Young, 2022: 583). None more evidently than the death of Ella Adoo-Kissi-Debrah, a 9 year old girl that lived near a known air pollution ‘hot-spot’ in London who suffered from repeated asthma attacks that correlated with air pollution spikes, before sadly dying during a particularly bad air pollution episode (Marshall, 2019). In this case, the matters of fact that air quality science provided were a part of – and a result of – a wider set of entangled social and political interests (Latour, 2004) that led to a step change in air quality action. Indeed, the ‘hard facts’ of air quality science were necessary but not sufficient in improving air quality. Put in other words, air quality scientists are:

> *“[…] roughly in the same position with regard to the natural world as travel agents stand with regard to summer holidays or property surveyors stand with regard to the value of a house. Their advice is the best available, but it does not constitute the final word”* (Collins and Yearley, 1992b: 385).

The original goal of my PhD had been to contribute to environmental justice (EJ) research focused on the distribution of air pollution, by making indoor air quality (IAQ) measurements to see if air pollution “follows the poor” indoors (Beck, 1999: 5). IAQ science remains comparatively “undone” (Frickel et al., 2010; Grandia, 2020) – a concept designed to identify science that is “unfunded, incomplete, or generally ignored” (Frickel et al., 2010: 445) – particularly in comparison to outdoors (AQEG, 2022). This is in spite of the fact that many people spend more than 90% of their time indoors (Klepeis et al., 2001), where air pollution concentrations can be greater than outdoors (AQEG, 2022), resulting in greater personal exposure indoors rather than outdoors (Vardoulakis, 2009). However, it was during the process of doing the IAQ science and becoming immersed in science and technology studies (STS), critical physical geography (CPG), and EJ literatures that some of the tensions in doing air quality science came into view. This included my own role in reinforcing how the air can be known, and defining what air pollution *is* in a given context. As such, my focus shifted from just the *doing of* air quality science, to both the doing of and *the science of doing* air quality science. Subsequently, I made the decision to foreground my own 'situatedness' in the doing of air quality science much more strongly across the chapters of this thesis, including the way a set of projects were set up, carried out, and how their results were represented. Cupples's (2009) call for more reflexivity in air quality science has, before this thesis, largely been left unmet. I would echo the points she makes for why it is needed, and what insights it might confer:

> *"Interrogating our conceptual assumptions, political motivations and embodied experiences and revealing our operational logics could be intellectually fruitful and could lead to an examination of a key tension in air pollution science which is why we are concerned about air pollution in the first place and what we aim to achieve through our work. Are we trying to protect or get back to a pristine nature? Is our work implicitly informed by notions of purity? Or do we believe in the notion of guidelines and safe levels, that some hybridity is acceptable? Do we believe that humans and the atmosphere have always been entangled, long before the industrial revolution or the advent of motorised transport? How then does the atmospheric environment become mobilised through scientific practice and knowledge? What are the philosophical underpinnings of particular ways of knowing the environment? And what are the political implications of such underpinnings?"* (Cupples, 2009: 215).

One of the important ways in which my immersion in STS literatures – in particular Actor-Network Theory (ANT)[2] – opened my eyes to how I was reinforcing how the air can be known was discovering the work that was being done by the air quality monitoring devices that I used. The NAQTS V2000 (hereafter V2000) was the IAQ monitor that I used across the fieldwork that comprises this PhD. My relationship with

[2] I describe ANT and my use of it in more detail in the Methodology chapter.

the V2000 was beyond that of merely a user, as it is a device that I co-created through my role as the CEO of a company called National Air Quality Testing Services Ltd (NAQTS). As such, the V2000 was a close companion of mine throughout all of the stages of my PhD: a companion of mine that embedded particular relations with the air throughout the papers that form this thesis, albeit in different ways. I am not the first to investigate the mediating role of air quality scientists and their instruments in the *production* of the air (e.g. Cupples, 2009; Garnett, 2017; Whitehead, 2009). However, I argue that my decision to both do *and* reflect on doing air quality science adds a novel perspective. Through foregrounding my own situatedness in the doing of air quality science, I add new insights into the multiple roles (or multiplicity) that a scientist inhabits in the doing of science. That is, the scientist is an actor that is influenced by an array of relations that go beyond an essentialist position of simply 'following the science'. In this thesis I do not take myself (or for that matter, any scientist) as a single static entity, but as multiple. I do this through bringing the mediating role of two identities to the table: 1) as a PhD researcher at Lancaster University and 2) as the CEO of NAQTS, the company that developed the V2000 (I go into more detail on these identities in the Methodology chapter). This contribution is important as the different relations that manifest these identities have the potential to differently influence the way that science is done and represented.

1.2. Thesis aims and research questions

It is the combination of my – reflexive – involvement in the production of the air, and focus on EJ that leads me to both describe the "partial, uncertain and challenging dimensions of measurement" but also to develop "different ways of engaging with air pollution science and governance, that highlight its social, ethical and political implications and effect" (Garnett, 2018). As such, the aim of this thesis is to analyse, in sociomaterial terms, the production of air quality, to explore how air quality knowledge is produced and critically engage with how we can reconfigure our relations with the air to begin to address air inequalities. In doing so, I ask:

1. How is knowledge about air quality produced and represented across different contexts and forms of air quality science? What dynamics and tensions emerge?

2. What relations and legitimisation processes are embedded within different forms of air quality science? What are the impacts on addressing air inequalities?

3. How can a hybrid approach to understanding air quality contribute to addressing air quality issues and inequalities effectively?

1.3. Thesis outline

This thesis is structured around three case studies of my direct involvement in the doing of different forms of air quality science. I use postnormal science (PNS) (Funtowicz and Ravetz, 1993) as a heuristic to describe the different forms of air quality science that were done. PNS, a normative framework for when "facts are uncertain, values in dispute, stakes high and decisions urgent" (Funtowicz and Ravetz, 1993: 744), splits scientific problem solving into three broad typologies: applied science, professional consultancy, and postnormal science. These typologies are depicted on an orthogonal representation that combines epistemic (*system uncertainty*) and axiological (*decision stakes*) variables. This is shown in Figure 1.1, which I have adapted from the original in Funtowicz and Ravetz (1993) to include the three papers that form the thesis. Systems uncertainty refers to the complexities of the system under consideration, including technical, scientific, and managerial aspects, and the ranges of possible outcomes (Turnpenny et al., 2011): as one moves higher up the y-axis there are more epistemological and ethical considerations. Decision stakes refers to all the costs, benefits, and value commitments that are involved in the issue: as one moves further along the x-axis there are more conflicting purposes.

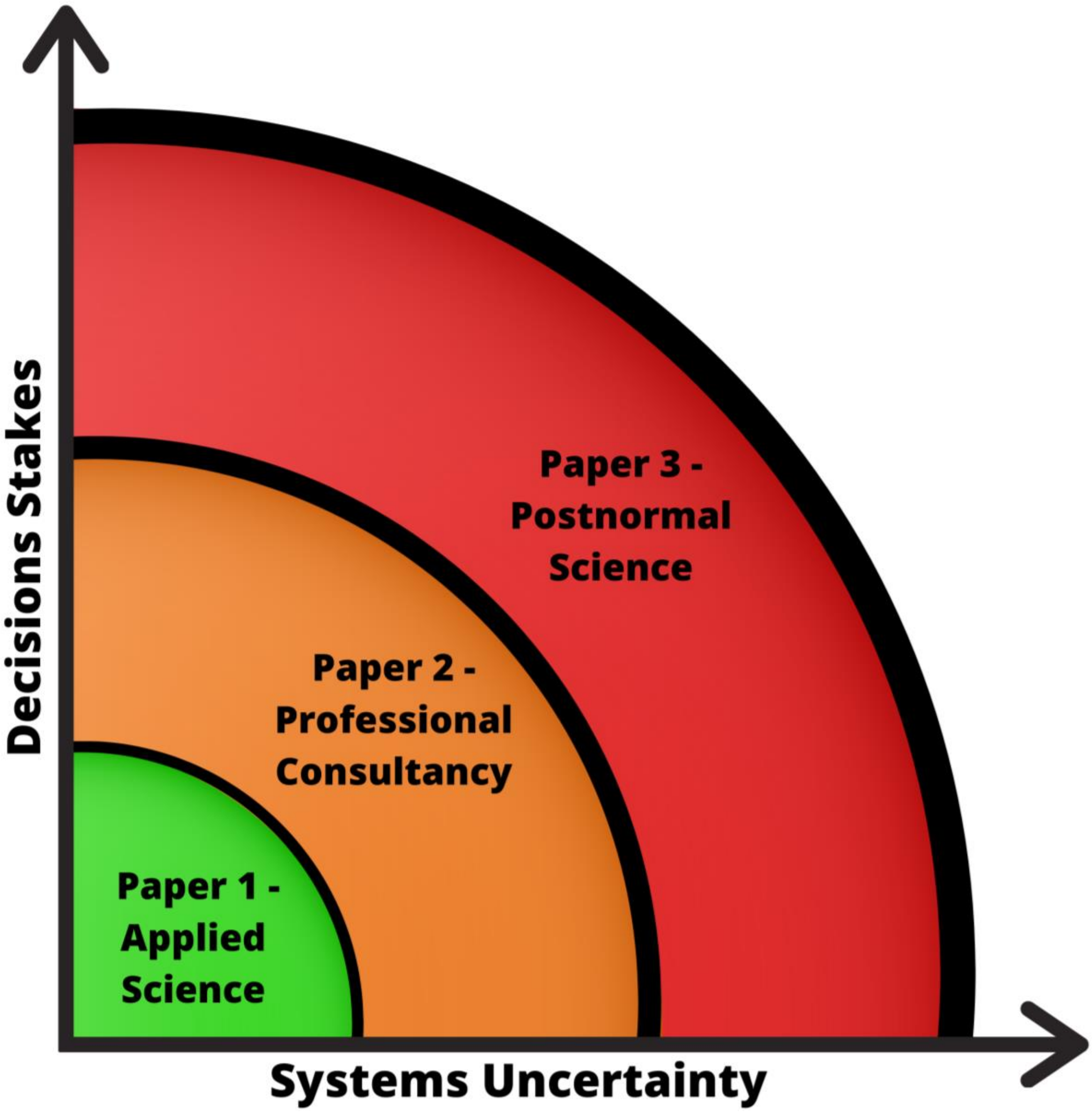

Figure 1.1: The postnormal science (Funtowicz and Ravetz, 1993) orthogonal representation that combines system uncertainty and decision stakes variables. I have adapted the figure to show where I engage with the three types of science across the papers that form this thesis.

In Paper 1, I challenge my own conventional account of the doing of PhD air quality science by autoethnographically analysing an indoor and outdoor air quality monitoring project that I led in a school.[3] This work maps onto the applied science typology of Figure 1.1: the systems uncertainties were low, as they were managed at the technical level through standard operating procedures (such as calibration, placement logics, and data filtering), and the decision stakes were also low, as there

[3] This is currently a working paper.

was a straightforward external use of the results, namely the preparation of a PhD chapter or a journal article. However, while the monitoring project itself might map onto the applied science typology, the paper challenges the representation of this typology of science as having low systems uncertainties and low decisions stakes. Through drawing upon ANT, this paper investigates the human and non-human actants[4] that influenced the questions the research asked, how they were investigated, and how the final representations of the air were generated and stabilized. In reality, low uncertainty, low stakes issues have now all but vanished (Ravetz, 2010). Nonetheless, for the purpose of heuristic, Paper 1 fits onto the Applied Science typology of Figure 1.1, especially given its focus on pulling apart a conventional account of the doing of PhD air quality science.

In Paper 2,[5] I draw upon a research-business project the sought to measure IAQ to assess the effectiveness of an air cleaning device in school classrooms pre- and post-the emergence of COVID-19. Using ANT alongside other more-than-human approaches to social inquiry, I interrogate how a network of 'science in action' became re-assembled to COVID-19, before relating the project to the wider – and ongoing – process of reassembling IAQ, asking how this might relate to questions of inequalities and responsibilities. This work maps onto the professional consultancy typology of Figure 1.1, the systems uncertainties were not only dealt with on the technological level as uncertainties also included methodological considerations involving more complex parts of the scientific problem-solving, such as reliability of data and implications of the results. Moreover, when looking at the decisions stakes this paper fits onto the professional consultancy typology as the project was carried out with external partners whose wishes were to be met, bringing with it more costs, benefits, and value judgments. As such, the project had deeper considerations based on where the burden of proof lies. Is something deemed safe until proved dangerous, or vice versa? Should absence of evidence of harm be interpreted as evidence of absence of

[4] ANT's terminology for actors, to designate its concept of relational agency. That is, actants are made to act by others.

[5] In press in *Ephemera: Theory and Politics in Organization*.

harm? These tensions were particularly prescient points when dealing with what is expected of air quality science during an airborne viral pandemic.

In Paper 3,[6] I reflect on a citizen science (CS) air quality monitoring project, both illuminating tensions in the dynamics of knowledge production and proposing a new framework for air quality research design and reporting, a framework I call critical air quality science (CAQS). This paper maps onto the PNS typology of Figure 1.1: when systems uncertainties and decision stakes are both high, fact-value distinctions are intertwined, forcing system level uncertainties to become enmeshed with ethical considerations (Funtowicz and Ravetz, 1993). In these situations, Funtowicz and Ravetz (1993) recommend shifting the focus of science from providing 'truth' to instead promoting 'relevance'. PNS calls for the inclusion of an 'extended peer community' (EPC) in science: traditional experts should be supported by, and work with those who the problem is actually affecting. The EPC is intended to enrich the processes of scientific investigation (and determine which data are relevant in a particular context) through the contribution of extended facts (EFs), principally in the form of local knowledge (Funtowicz and Ravetz, 1993). Paper 3 maps onto the PNS typology of Figure 1.1, as it deployed an EPC (and its EFs) via a CS project. In this paper, I combine the doing of 'relevant' air quality science, by focusing on evidencing outdoor traffic air pollution finding its way indoors, with my CAQS framework proposal (which establishes a critical framework for doing relevant science), and further academic studies to inform other air quality scientists how to meaningfully engage in air quality CS (and other forms of air quality science for that matter). Using my CAQS framework, and drawing on interviews with the involved citizen scientists, I illuminate tensions in the dynamics of CS knowledge production, outlining the implications of these tensions for air quality research design and reporting, and EJ.

Before delving into the papers that form the main part of this thesis, I first include Literature Review and Methodology chapters. While the papers are self-contained, and as such engage with and incorporate the relevant literatures and methodological discussions, I include stand-alone chapters to position my contributions within the wider academic canon. In the Literature Review chapter, I position my work in relation

[6] Published in *Local Environment* (Booker et al., 2023).

to three core literatures: CPG, the air's sociomateriality, and EJ. In the Methodology chapter, I outline the theoretical, ontological, and epistemological underpinnings of my focus on the doing of air quality science, including a summary of the development of the sociological gaze on scientific practice; my use of ethnographic methods, including the mobilisation of my different identities; and my use of ANT, which is used in varying ways in two of the three papers that form this thesis. After the three papers, I have a Conclusion chapter where I provide a summary of the findings, contributions, implications, and limitations of the papers. Moreover, I return to answer the research questions outlined in the Introduction chapter, relate the implications of my findings on constructing future diverse claims of EJ, and make recommendations for future research.

1.4. Contributions

There are some specific contributions that are mentioned within the papers, but the overall thesis makes five wider contributions.

First, I build upon previous work investigating the mediating role of air quality scientists and their instruments in the *production* of the air (e.g. Cupples, 2009; Garnett, 2015, 2017, 2020; Whitehead, 2009). Through both doing the science, and later reflecting upon the process, I contribute a novel perspective drawing upon my own multiple and shifting identities: I am involved in the development and commercialisation of air quality monitoring instrumentation, the practices of air quality science, and the critical reflection that constitute this thesis. I also widen the scope of the practice of air quality science from multi-disciplinary science, to include industry-academic and CS. I also provide insights into how "the scientist-instrument-data relations used to configure air pollution as a scientific entity" differ across different types of air quality science, and differently "become the space where decision-making and air politics play out" (Garnett, 2015: 247).

Second, I contribute to 'hybrid' ways of doing air quality science, through both making visible the material air, and its entanglement in political, social, and economic relations. I directly answer Cupples's (2009: 212) call to use ANT in air quality science "to move us beyond unhelpful dichotomous divisions between realism and social constructionism or between science and culture." Specifically, I use ANT to make visible the range of different relations that are obscured during the normal reporting of air quality science, and to think through air quality's sociomaterial instability that happened while doing air quality science.

Third, and related to this hybridity, I develop a new CAQS framework to study air pollution's sociomateriality (Paper 3) and to provide insights into how air quality science could be reassembled to be more environmentally just. Moreover, while I do state that my aim in constructing CAQS is not to simply recreate CPG for air quality science, I do bring air quality within the scope of the CPG subdiscipline. This provides a platform for further work to be done to study air pollution's sociomateriality, whether that is under the CPG or CAQS umbrella.

Fourth, through focusing on IAQ I bring the built environment to the fore, contributing to the critical scholarship of IAQ. In both the natural and social sciences the indoor environment is comparatively less well understood (AQEG, 2022; Biehler and Simon, 2010). In this thesis, I bring *hybrid* air quality science indoors, advancing both material understandings of IAQ (through making measurements), but also IAQ's human (and non-human), political, social, and economic relations. I do this most clearly in Paper 2, where I combine the measurement of IAQ in 20 schools with a focus on how the process of doing the science was reassembled in response to the emergence of COVID-19. This includes a critical perspective on wider processes of reconfiguring IAQ, including what it might mean for a more critical IAQ science in the future. In doing so, I answer calls for further theorising of the air indoors (Biehler and Simon, 2010) and the call for a political ecology of urban air that addresses the air within interior spaces (Graham, 2015).

Fifth, through examining the mediating roles of my own identities in doing air quality science, I investigate an emerging aspect of EJ, namely epistemic justice – the extent to which people are respected in their capacity as knowers. This aspect of justice has received considerably less attention in environmental science. This omission is of particular importance as the "structural authority afforded to science and scientists in environmental politics" (Ottinger, 2017a: 42), has the effect of "legitimis[ing] certain kinds of inquiries, ideas and methods", in particular over what counts as evidence of potential harm, meaning that “we act upon systems in particular ways” (Tadaki et al., 2015: 165). This aspect of justice is particularly important in the doing of air quality science, as “much of the remedy to epistemic injustice lies in the attitude of the listener” (Ottinger, 2017b: 96), highlighting an important role for air quality scientists in representing different groups’ concerns about air pollution. This epistemic justice frame forces air quality scientists to ask “who the representation benefits relative to other kinds of understandings” (Tadaki et al., 2015: 165).

2. Literature Review

In this chapter I situate the papers that form the core of the thesis in three main areas of the wider literature: critical physical geography (CPG), studying air pollution's sociomateriality, and environmental justice (EJ). I both highlight the groundings of some of the specific contributions in each of the papers, but also the wider contributions of the thesis.

2.1. Critical Physical Geography

Built on the foundations of political ecology, science and technology studies (STS), and land use/land cover change research (Lave, 2018),[7] the CPG approach aims to integrate the social and natural sciences in the pursuit of EJ by studying the socio-material impacts of power relations with a deep knowledge of the material environment (Lave et al., 2014). Here CPG is answering repeated calls for integrating human and physical geographies (e.g. Goudie, 1986; Massey, 1999; Clifford, 2002; Harrison et al., 2004; Bracken and Oughton, 2016). The CPG field is relatively new and can be considered to be somewhat disparate, with few scholars distinctly positioning themselves as 'critical physical geographers'. Nonetheless, CPG scholarship is wide ranging,[8] including in geomorphology (e.g. Wilcock, Brierley, and Howitt, 2013), atmospheric science (e.g. Johnson, 2010; Thornes and Randalls, 2007), hydrology (e.g. Lave, Doyle, and Robertson, 2010; Lane et al., 2011) and soil science (e.g. McClintock, 2015). However, it has yet to fully be realised for air quality science despite some notable exceptions (e.g. Clifford, 2019; Kroepsch and Clifford, 2021). Part of the reason for this omission is likely due to air quality science sitting across disciplines other than geography, including chemistry and physics. As such, one of the contributions of this thesis is that I bring air quality within the scope of the CPG subdiscipline. Moreover, in Paper 3 I also develop a critical air quality science (CAQS)

[7] Lave, Biermann, and Lane (2018) stress that while CPG is different to these three precursors, CPG is in conversation with these field and intends to sit alongside them, rather than replace them.

[8] See Lave, Biermann, and Lane (2018) for a more exhaustive list of CPG references.

framework, which heavily draws upon CPG, to speak to these other disciplines that do air quality science. There is also a wealth of scholarship that is not formally referred to as CPG that demonstrates the potential of the framework (Lave et al., 2014). For example, in air quality science specifically there is the work by Lane et al. (2022), which traces how unequal patterns of air pollution in 202 cities have been shaped – and continue to be shaped – by discriminatory mortgage practices in the 1930s. This is but one example of the potential fruitful application of CPG type approaches to air quality science.

While CPG encompasses a diverse range of fields, methods, and epistemologies, it is centred on three main intellectual tenets (Lave, Biermann, and Lane, 2018):

1. **Hybridity –** landscapes, that is something that is not just rural and local (e.g. hills!) but a 'hybrid' that is created both by nature and humans (Allen, 2011), are shaped by human actions and structural inequalities that are neither external to nature, nor purely social. Rather, they are co-produced by the materiality of nature resulting in eco-social systems.
2. **Reflexivity –** the structural inequalities that shape landscapes also define who studies them, the questions asked (or ignored), the way research is conducted, and findings.
3. **Power and Justice –** The knowledge produced by research is not apolitical, and always has an impact.

In Paper 3, I build on these tenets to develop my CAQS framework. In the paper I briefly explain the tenets and their potential application for air quality science. However, in this section I will take each of these tenets in turn, detailing their genealogy and practice in the CPG literature, before explaining how CPG's use of these tenets is different from and builds on its foundations in other literatures.

2.1.1. Tenet 1 – Hybridity

CPG advocates both for a 'critical turn' in Physical Geography, and a 'physical turn' in Critical Human Geography (Lane, Biermann, and Lave, 2018). This is because at the core of CPG's argument is that in the age of the Anthropocene we cannot rely solely on explanations from physical or human geography as the material world is co-produced by social practices and environmental processes (Lave et al., 2014). For example, "people have fundamentally altered the terrestrial carbon cycle and other biogeochemical cycles, modified and appropriated water cycles, and pushed species into extinction" (Urban, 2018: 51).

This tenet has its roots in political ecology and land use/land cover research. CPG pays homage to early scholarship in the field of political ecology (e.g. Watts, 1983; Blaikie, 1985) that provided an interdisciplinary account of the politics of environmental science through pairing strong normative discussions on EJ with quantitative material evidence (Lane, Biermann, and Lave, 2018). It is important to note that CPG and political ecology do differ. Lave et al. (2018) argues that political ecology has largely left its interdisciplinary approach behind, deploying the natural environment as a field on which political research happens, rather than an important factor itself (Walker, 2005). However, CPG is not just about 're-materialising' political ecology, but is about deepening that integration to provide more balanced physical and social environmental research (Lane, Biermann, and Lave, 2018). Likewise, the land use/land cover literature which investigates the effects of contemporary and historical effects of human activities on ecosystems is argued to be a good demonstration of integrated environmental research that brings together a broad array of biophysical and human qualitative and quantitative data. For example, Robertson et al. (2018) examine how historical social practices and land-use effects both contemporary forest ecosystems physical form, and their social management. However, land use/land cover approaches differ from CPG principally in their commitment to reflexivity (a tenet I turn to next). As Robertson et al. (2018) argue, for the majority of land use/land cover researchers reflexivity is not common practice.

There is a wealth of good examples of hybridity in CPG. To exemplify with a few, Johnson (2010) combines political economy and physical geography to explore how the physical processes of climate change have reconfigured social practices to encourage new regional 'rent-seeking' strategies in the Arctic, which may in turn feedback and exacerbate future global warming. Lave et al. (2010) examine how market-led approaches to stream restoration have embedded perverse financial incentives that have shaped streams in particular ways. Through deploying natural and social science approaches together, CPG scholars argue that we get a more comprehensive understanding of the socially and naturally co-produced landscapes we live in. This provides a robust response to the implications of the Anthropocene, as landscapes are deeply shaped by human actions (Lave, Biermann, and Lane, 2018).

2.1.2. Tenet 2 – Reflexivity

The second tenet of CPG focuses on scientific practices and its inseparable links to social, political, and economic relations that affects what is researched, the way it is researched, and the results of research. This includes how research is influenced both internally (e.g. one's own identities and interests) and by external factors (e.g. funding and wider academic agendas) (King and Tadaki, 2018). A CPG framework "insists on reflexivity in research and attention to the ecosocial consequences of knowledge production" (Biermann et al., 2020: 816). In doing so, it advocates for researchers to be reflexive to fully understand why one is using certain scientific concepts and theoretical frameworks, what relationships they are legitimising (Tadaki et al., 2015), and ultimately what worlds their methods are making visible (Law and Ruppert, 2013).

The concept of reflexivity is not an invention of CPG; it has a long history both within geography and in a range of other disciplines including STS.[9] Indeed, reflexivity has firm roots in STS through looking at the range of social factors that can help to explain how scientific facts are constructed. However, CPG is clearly distinct from STS, going beyond taking natural science as an analytical object to *doing* natural science (Lave et al., 2014). This is a key contribution of this thesis.

Braun (2021: 21) provides a great example of reflexivity in the CPG literature through dissecting the practice of remote sensing in land use/land cover data, arguing that the norms and practices for more accurate data can lead to "more accurate results" but results that lack "environmental meaning". Another example is Blue and Brierley (2016), who interrogate geomorphology and suggest that its development as an

[9] A point I will explore in the Methodology chapter looking at the sociology of scientific knowledge (SSK) framework.

‘applied science’ has embedded values of pragmatism that fundamentally shaped the questions asked, the data collected, and the answers produced.

2.1.3. Tenet 3 – Power and justice

The third tenet, power and justice, can be considered as an extension of the principle of reflexivity and is concerned with examining the social and physical impacts of scientific knowledge production. Law (2018) illustrates clearly how scientific fieldwork impacts biophysical environments, social relations, and socioecological imaginaries.[10] In terms of biophysical environments, the impact can be quite simple: “geologists remove rock samples and fossils. Geomorphologists, glaciologists, and hydrogeologists drill bore-holes” (Law, 2018: 91). While air quality science may not be as directly impactful as removing matter and – simply put – digging holes, it can still change the biophysical environment by “changing terminology, data sets, classification systems, and management regimes” (Law, 2018: 91). In terms of social relations, human interaction is a large part of critical human geography, and researchers inevitably cannot interact with everyone in a community. The question arises whether these disparities in relations may benefit – or harm – some more than others. In other words, “research does not drape itself across the landscape like a blanket. Rather, it produces uneven contours as it differentially enrols and affects humans and nonhumans” (Law, 2018: 90). In terms of socio-ecological imaginaries, simply by studying something, we give weight to it as being something worth studying. This added weight may influence people involved in research to act differently. This theme will be particularly explored in Paper 3 in my fieldwork with Better Old Swan on a citizen science project and changing perceptions on where air quality exposures can occur.

While these social and physical impacts may be important in and of themselves, CPG contends that since scientists are not in an ‘ivory tower’ disconnected from the societies that they inhabit, but tangled in an array of social relations, the production of scientific knowledge is inherently political (King and Tadaki, 2018). Therefore, the choice is not between being political or apolitical, but among a range of political

[10] A term “concerned with envisioning (and progressing) the transformation of relationships between human society and the rest of the planetary environment” (Herbert, 2021: 374).

positions (Law, 2018). With this in mind, CPG scholars argue that scientists should think carefully about the impacts of their research, including principally who will benefit from the knowledge produced and who will be harmed (Law, 2018).

CPG's dialogue with the field of STS has significantly influenced this tenet, in particular STS's emphasis on the social element of scientific knowledge production, which argues that no science or scientist can be considered apolitical because they are themselves a part of society (Haraway, 1988; Latour, 1999). Thornes & Randall (2007) are a good example of this approach in the CPG literatures, as they reflect on the implications of the commodification of the atmosphere. They argue that researchers should be aware of the consequences of the outputs of their research. For example, in air quality science and business, data and/or predictions about the atmosphere are increasingly commodified, whether that be for 'smart cities' and/or automating traffic management systems, or as part of the management of building ventilation systems to minimise COVID-19 transmission.

These tenets of CPG have contributed greatly to my attempt to apply a hybrid approach to air quality science, as an attempt to address both air quality issues and air inequalities. As I have already said, while I do not position myself explicitly as working under the CPG moniker in this thesis, I certainly speak with it, most concretely in my development of CAQS.

2.2. Studying the air's sociomateriality

The study of air quality is often bifurcated into its social and material components (a point I pull apart in Paper 3). As Cupples (2009: 210) argues "while there is some overlap between these two literatures, the scientific dimensions of environmental problems are often studied separately and by different scholars from the cultural dimensions of these same problems." Notwithstanding this bifurcation, the natural element tends to dominate: Graham (2015: 194) proclaims that "despite the wider public discourses of air emergency in the world's cities […] 'Technical', depoliticised, medicalised, positivist, physical geographic and public health policy discourses still overwhelmingly dominate the field." Indeed, the majority of air quality research is typically focused on quantifying air pollution concentrations (both at a single point, and how they change over time), attributing them to a source or process, and/or speculating about potential effects on human health and wellbeing, and economic growth (e.g. WHO, 2021; World Bank and Institute for Health Metrics and Evaluation, 2016). This research is expressed quantitatively in a host of statistical patterns, correlations, and regressions. However, there has been a growing element of scholarship on the sociocultural dimensions of air quality, shifting "the focus from mainly quantitative, statistical and 'objective' analyses, towards also including more subjective understandings of people's relation to air" (Kenis and Loopmans, 2022: 563). I turn to these sociocultural factors now, before I turn to hybrid studies of the air, and finally hybrid studies of *indoor* air.

2.2.1. Sociocultural air

There have been a large range of social science studies into how we come to know – and act upon – the air, and its relation to systems of governance. This is not to say that this is an exhausted field. Indeed, there have been periodic calls for more work into the political ecology of air pollution (e.g. Véron, 2006; Buzzelli, 2008; Graham, 2015). In this section I briefly describe some of the main literature and developments, and how my work draws upon them.

Work on public risk perceptions of air pollution has highlighted that people draw on informal or 'lay' knowledges to assess air quality, including the smell and taste of the air, and prevalence of various health symptoms (Bickerstaff, 2004; Bickerstaff and Walker, 1999, 2001). Moreover, these works have shown that knowledges of the air are intertwined with local place identities, including, for example, historical associations with heavy industry (Bush et al., 2001), and cultural identities around masculinity and nationality (Cupples et al., 2007). Furthermore, Altman et al. (2008) found that participants personal and collective environmental history influenced their embodied narrative or 'exposure experience' and that scientific understandings and embodied experiences emerge through one another. The use of qualitative socio-cultural analyses of air pollution perception has not developed considerably since these earlier works (Noël et al., 2021: 9). However, a recent review article (Cori et al., 2020: 20), based more on quantitative assessments of risk perception has confirmed the findings of Bickerstaff (2004) that "perception of risk is multi-dimensional and influenced by complex social, political, and cultural processes." Alongside these lay ways of knowing the air, a growing number of scholars have also investigated affective, embodied, and attuned encounters with, and ways of knowing the air (Adey, 2013; Calvillo, 2018; Calvillo and Garnett, 2019; Choy, 2012; Hauge, 2013; Kenner, 2021; Oxley and Russell, 2020; Shapiro, 2015).

There has also been a growing engagement with the role of both academic and government science[11] in framing what it means for the air to be polluted, and how the air is governed. Air quality governance is "typically dominated by technical expertise and scientific knowledge" (Da Schio, 2022: 30). This in part at least because "even though we generally know air's chemical composition […] we almost never perceive it." Indeed, "the possibility of actually perceiving air may be understood as inherently intertwined with the technical infrastructures that produce our relation to it" (Weber, 2021: 176). This is obviously not the case for all air pollutants, such as those that can be perceived through forms of sensory experience, as discussed above. However, for example, the pollutant that I measure throughout my PhD, ultrafine particles, are literally invisible, so measurement is critical to materialise it in discourse. Whitehead (2009) outlined the development of technical infrastructures to measure the air in the UK, arguing that it was the "construction of a scientific apparatus of, and for, government" (Coe et al., 2012: 1058). Barry (2002: 268) would further extend this to suggest that these technical infrastructures of measurement also create a "conduit for the cross-contamination of the economic and the political." Whitehead (2009: 102) argues that this technical infrastructure was not "guided purely by abstract rationality" but that it was also "structured by the material limitations associated with the instruments of science", as well as:

> *"Acts of whimsy by governmental or scientific authorities, indiscipline by observers or the simple banality of everyday events. In the latter category come the […] London County Council member driving away with the pollution monitoring equipment temporarily suspended on the car roof*

[11] I separate academic and government science here. However, in practice the "boundaries between the scientific and the government apparatus are blurred" (Da Schio, 2022: 30).

> *before it crashes to an inevitable shattering landing"* (Coe et al., 2012: 1059).

Whitehead clearly illustrates the role of non-human actants to make a difference through the fabrication of the Committee for the Investigation of Atmospheric Pollution in 1912, that was founded to establish a systematic framework for air pollution monitoring in the UK. Here Whitehead illustrates the Committee's problematisation and definition of what constitutes air pollution, which essentially acknowledges the limitations associated with existing instruments for measuring air pollution:

> *"The Committee's interpretation of the term 'pollution' relates to such matter, solid, liquid, or gaseous, as reaches the surface of the earth or falls upon the buildings, either by its own gravity or with the assistance of falling rain"* (Whitehead, 2009: 101).

Air pollution's definition as a something that "reaches the surface of the earth" reflected the period's lack of technology to measure suspended air pollution. The eventual choice of an instrument that could meet the scientific requirements of accuracy, repeatability, and reproducibility, along with the government demands of durability, mobility, and mass production, led to the selection of a device that could measure deposited pollution. This measurement was even justified by stating that suspended air pollution will eventually become deposited pollution. This justification clearly had to ignore gaseous air pollution. These material limitations help to explain how air pollution is "a complex and ever-changing category of analysis that has, at different times, incorporated germs, disease, dust, pollen, grit, smoke, fog, soot, sulphur dioxide, lead, radioactive materials, pesticides, chlorofluorocarbons, carbon dioxide and other visible and invisible substances" (Whitehead, 2009: 2). In Paper 2, I build on this point to show how air pollution is not a stable form of knowledge, through following the arrival of COVID-19 into school classrooms around England and Wales.

Focusing on the practices of scientists, Garnett (2016, 2017, 2020) has shown the variety of ways that scientists come to know and materialise air pollution's multiplicity. Through ethnographically studying air quality monitoring and modelling practices, Garnett (2016) follows the process of stabilising and producing air quality data. This is an especially important activity as air quality data has “actively shaped what constitutes air, and how air is experienced and engaged with” (Garnett, 2016: 2). However, in Paper 1 I problematise this monitoring/modelling distinction using the Actor-Network Theory (ANT) concept of circulating reference, arguing that if you go deep enough there is always a model. Garnett (2016) also outlines how scientists have their own affective or embodied ways of knowing and relating to the air, problematising the designation of lay knowledge only belonging to laypersons, a tension I investigate in Paper 3, contesting designations of ‘insiderness’ and ‘outsiderness’. Garnett (2017: 920) extends this work by looking at how scientists work across disciplines, showing both how different disciplines’ ways of knowing air pollution defined their perception of what was ‘good data’ to represent it, but also how these “different ontologies of air pollution were at once contested and made to coexist.” I draw heavily upon these works in my thesis, both to trace how the air is constructed, in sociomaterial terms, and the multiplicity of the air as a research object. However, there are some significant differences, as I go further by doing the science that I then reflect on to provide a hybrid perspective, as well as extending these insights to citizen science and research-business science.

The matters of fact that science produces are important. However, social science studies have also outlined the wider array of social and political actors that mobilise the matters of fact that science generates to turn issues into public ‘matters of concern’ (Latour, 2004). For example, Kenis and Barratt (2021) highlight the role of the media in staging air pollution as a matter of concern. Likewise, Gross, Buchanan, and Sané (2019: 85) outline the role that government policies, including air quality management areas, have on framing socioecological imaginaries on how to respond to air pollution, leading to certain modes of tackling air pollution to become “institutionally stabilized and publicly performed.” Moreover, Marzecová and Husberg (2022) argue that numerical representations of the air, such as $PM_{2.5}$ and air quality indexes do not only serve as a mode of making visible the air’s concentrations of certain pollutants, but also as a mobilisation tool that shapes citizenship practices.

2.2.2. *Doing hybrid air quality science*

One must reject purely 'social' explanations for the air, as "just as natural science approaches tend to exclude human behaviour, so [..] sociological perspectives tend to exclude the physical and environmental from their accounts of human change" (Lutzenhiser, 1994: 71). An increasing number of contributions across the social sciences have embraced the return to matter, such as under the rubric of new materialism (Coole et al., 2010), and more-than-human (Whatmore, 2002) approaches. These approaches have aimed to both "'socialize the Anthropocene'" but also "'geologize the social'" (Clark and Yusoff, 2017: 6). Part of this embracement of the material and the non-human has been the proliferation of the concept of 'hybrids' which can be seen as an attempt to upheave "the binary terms in which the question of nature has been posed" to recognise "the intimate, sensible and hectic bonds through which people, organisms, machines, and elements make and hold their shape in relation to each other in the business of everyday living" (Whatmore, 1999: 26).

This has been reciprocated in the study of the air, with the air's hybrid nature being widely documented (e.g. Cupples, 2009; Nieuwenhuis, 2016; Walker, Booker, & Young, 2022; Kenis and Loopmans, 2022). This hybridity has been most precisely articulated by Cupples (2009: 209) who calls for an air quality science that can "simultaneously acknowledge the physicality and seriousness of air pollution, but also pay attention to the places and spaces in which air pollution (knowledge) is produced and performed." Cupples (2009) outlines intersecting priorities that she proposes for air quality science including abolishing nature/culture divides, abandoning social constructionism and realism, taking non-scientific knowledges seriously, and being more reflexive. Despite its great value, this call has not – until this thesis – been explicitly met with great enthusiasm within air quality science. That is not to say that there are not existing studies that do air quality science that could be called hybrid. However, they do not explicitly label themselves as such. For example, Yearley et al. (2003) trialled participatory modelling approaches combining local knowledges, through community mapping exercises, with computer models to develop new ways of doing local governance of air quality. Moreover, this is also not to say that there is much more recent research that equally could be called hybrid air quality science. For example, Da Schio (2022) both made participatory air quality measurements using wearable sensors, as well as reflected on how the air interacts materially and symbolically within the urban environment, and people's daily lives. Nonetheless, one of the contributions of this thesis is directly taking up Cupples's (2009) call. This is most clearly articulated in Paper 3 where I develop a CAQS framework to do hybrid air quality science. However, this hybrid approach resonates in different ways across the thesis. To demonstrate this, I describe the priorities Cupples (2009) outlines and explain how I incorporate these elements into my thesis. As with CPG, there are some significant overlaps between my use of Cupples (2009) and the CAQS framework I develop in Paper 3. Perhaps most clearly in the fact that I use the concept of hybrid as one of the tenets of research that CAQS should do!

Cupples's (2009) attempts to abolish nature/culture divides by calling for both letting go of nature and our humanism. Cupples advocates for treating "the atmospheric environment [..] as both an actor as well as a network" (Cupples, 2009: 213). This entails not seeing the air as solely out-there, a static backdrop upon which the social happens. Instead, she calls for seeing the air (not just it's diminishing through air *pollution)* as a product of sociomaterial relations. At the same time, she calls for not privileging humans in our accounts, as the air is a relational achievement between "discourses, scientists, instruments, bodies and pollutants in which the pollutants themselves are active subjects in the creation of particular geographies" (Cupples, 2009: 214). In doing so, she calls for an inclusion of non-human agency in our accounts of the air, which "might mean living more openly with the messiness and contingencies of atmospheric science (in our journal articles as well as in our labs) and acknowledging how some of the nonhumans we study resist being disciplined and ordered" (Cupples, 2009: 214). I show this messiness and contingency in Paper 1 and Paper 2, where I show the full range of factors that influence how the air quality science was done, but also how the sociomaterial definitons of IAQ changed with the arrival of a new air pollutant, SARS-CoV-2, the virus that causes COVID-19.

Through abandoning social constructionism and realism, Cupples (2009: 214) advocates for adopting a 'hybrid' position between them so that "we can also abandon the distinction between facts (which are seen to belong to scientists) and values (which are seen to belong to policymakers and non-scientists)." To do this, Cupples (2009) explicitly argues for using ANT to erase the unhelpful realism/social constructionism and nature/culture dichotomies constructed in air quality science. I do this most clearly in Paper 1 and Paper 2 through using ANT (in different ways) to make visible relations that are typically concealed during air quality science to provide a more complete view of the air's sociomaterial construction. I discuss ANT, and my use of it, at length in the Methodology chapter.

Cupples's (2009) final priority for air quality science is being reflexive. Cupples (2009: 215) argues that because of air quality science's key role in mediating what we come to know about the air, we should recognise that air quality science is "a power laden intervention in the relations between humans and nonhumans, rather than an objective, value- free problem-solving exercise." This principle of reflexivity is strongly reflected across the thesis: Indeed, I will expand upon this in the Methodology chapter. Moreover, it is a tenet of research that I include in my CAQS framework developed in Paper 3.

2.2.3. An air of mystery: Indoor air quality

Despite the significant work both on material and sociocultural dimensions of air quality, there are still significant gaps related to indoor air quality (IAQ). Across both the natural and social sciences, IAQ is comparatively less studied (AQEG, 2022; Grandia, 2020). Materially, recent reports from the UK's Chief Medical Officer (Whitty and Jenkins, 2022) and the Air Quality Expert Group (AQEG, 2022) have highlighted both how IAQ is much less studied than outdoor air quality and how a "better understanding of how we can prevent and reduce indoor air pollution should now be a priority" (Whitty and Jenkins, 2022: i). These calls have been around for a long time[12] but have grown recently, perhaps as established IAQ matters of fact have morphed into a matter of concern in response to COVID-19's emergence.

Likewise, socially there has been much less research on the air of indoor environments. This is not to say that there have been noteworthy contributions: on modes of knowing the air indoors mediated through scientific practices (Garnett, 2020), embodied experience (Altman et al., 2008; Shapiro, 2015), and practices (Hauge, 2013); on how uncertainty is politically weaponised along lines of gender (Grandia, 2020; Murphy, 2006); and agenda setting papers on research needs for a

[12] Something that I am very well aware of having been involved in IAQ science since 2015!

political ecology of IAQ (Biehler and Simon, 2010; Graham, 2015). Biehler and Simon (2010: 174) outline how social science has largely treated "indoor spaces and the things in them as passive and self-contained […] rather than having the potential to reshape nature and social relations." A perplexing point given that many humans spend the majority of their time in indoor environments (e.g. Klepeis et al., 2001). As such, Biehler and Simon (2010) argue for more research into how technologies shape relations indoors, how indoor environments manifest as sites of power and governance, and the fluid boundaries between indoor/outdoor environments. All points that I pick up across the papers that form this thesis. Moreover, Graham (2015) as part of his wider call for a political ecology of urban air calls for understanding specific indoor practices and sociotechnical infrastructures, such as the *conditioning* of air (both in terms of air conditioning and filtering and ventilating) within interior spaces. In particular as a site of environmental (in)justice, as some – but not all – can go into conditioned indoor spaces to escape the city's air pollution: something Graham (2015: 204) refers to as 'the layered politics of urban atmospheres."

Through focusing on IAQ, I bring the indoor environment to the fore in this thesis, contributing to its critical scholarship, and advancing both social and material understandings of IAQ; in other words, a hybrid understanding of IAQ. I do not claim to be the first to provide something of a hybrid perspective on IAQ. For example Hofflinger, Boso, and Oltra (2019) compared public perceptions of indoor and outdoor air quality, finding that the home was seen a 'sanctuary' from polluted air, regardless of the actual concentrations of air pollution. Also, Heydon and Chakraborty (2022), focusing on wood burning stoves effects on IAQ, combined IAQ measurements with surveys, research diaries, and qualitative interviews to show how relations between IAQ sensor data and perception of risk were mediated through socio-cultural knowledges. However, I would argue that I am the first to explicitly label my work as hybrid IAQ science. Moreover, notwithstanding there undoubtedly being countless other studies that combine social and natural sciences methods to provide a more 'holistic' view on IAQ, I would argue that I am the first to take a deeper conception of hybrid air quality science that aligns more closely with the tenets outlined by Cupples (2009). In particular, one that embraces reflexivity to unpack air quality science's role in framing how we come to understand and act upon the air. An especially important point as "human and ecological processes can interact at levels that cross the boundaries of disciplinary frameworks" (Da Schio, 2020: 24), meaning that research needs to be hybrid all the way through, and not simply bolted on physical or social science methods.

Accepting air quality as a hybrid phenomenon requires one to think carefully about the epistemological boundaries that are established in science, their relevance, and whether different modes of science might be better. In the following section I start to open up these tensions through looking at science's relation to questions of environmental justice, in particular through doing citizen science.

2.3. New strands of environmental justice: Epistemic justice

Elucidating the exposures and experiences of vulnerable communities to poor air quality been a key focus of the environmental justice (EJ) movement. This has typically focused on demonstrating the extent to which air pollution is equally — or unequally — distributed across particular defined social groups. This is commonly referred to as distributive justice (Schlosberg, 2007). Research has largely focused on distributive justice and ambient air pollution (AAP)[13] and is commonly translated into exposure-based assessments of likelihood for health consequences expressed quantitatively, in a host of statistical patterns, correlations, and regressions. While distributive justice may be central to EJ claim making (Schlosberg, 2004), our understanding of what constitutes and causes EJ is more complete when other elements of EJ are utilised (Walker, 2012). However, "the scholarship which […] investigates the processes underlying the unequal flows of air pollution, its root causes and implications is much less developed" (Kenis and Loopmans, 2022: 564), despite significant developments upon the distributive conception in the last few decades. Schlosberg (2007) details three other types of EJ that have emerged: procedural justice, justice as recognition, and a capabilities framework. I now take these in turn.

Procedural justice understands justice as the "fair and equitable processes of a state" (Schlosberg, 2007: 25), principally with a focus on regulation, decision-making processes, and the practices of government. Procedural justice is not intended to

[13] This term is often used in air quality science to talk about outdoor air quality: I use the two terms interchangeably in this thesis.

serve only as an explanation for why certain patterns of injustice have emerged, rather it is considered to be an element of justice making in its own right asking questions of the availability of environmental information; the extent to which involvement in decision-making processes is available, and meaningful; and the ability to challenge decision-making processes (Walker, 2012).

Justice as recognition is closely connected to distributive and procedural justice but is distinct in its focus is on the damage that is inflicted on individuals and communities in terms of insults, stigmatisation, and devaluation. These misrecognitions go beyond the realms of the state and are deeply embedded in culture. Misrecognitions can be based on gender, race, class, or a myriad of other social categories. As with procedural justice, recognition is seen both as a subject of injustice, but also as a condition of justice: misrecognition is an injustice not only because it does people harm, but also because it is the foundation for distributive injustice and a fundamental hindrance to effective participation in decision-making (Schlosberg, 2007).

The capabilities framework (Sen, 1999, 2009) can be understood as both a distinct form of justice, and an integrative framework that combines many of the elements of distribution, procedure, and recognition. The capabilities framework is concerned not with the distribution of environmental goods or externalities *per se*, but rather the capabilities of people to actually achieve the lives they value, rather than merely a right to do so.

These extensions to our understanding of EJ are comprehensive. However, they have not adequately addressed how knowledge counts in the practice of environmental decision making (Ottinger, 2017b). As such, whose knowledge is legitimate in the contestation of environmental problems has become a new frontier of the EJ movement, with theories of "knowledge justice" (Allen, 2018; Egert & Allen, 2019), and "epistemic justice" (Fricker, 2007). Indeed, Ottinger (2017b: 96) argues that "'epistemic justice' should be considered a fifth aspect of environmental justice." Epistemic justice investigates the extent to which people are respected in their capacity as knowers and has two key concepts: *testimonial injustice* and *hermeneutical injustice.* Testimonial injustice seeks to explain how laypersons are precluded from full participation in the processes of fact-collecting through institutionalised misrecognition of their credibility.

For example, in contesting poor air quality the data from scientists are typically accepted by policy makers, whereas the everyday observations and tacit knowledge of local communities are often held as suspect or simply ignored. Fricker (2007) asserts that this asymmetry can work in both directions, whereby misrecognition can give a 'credibility excess', meaning someone receives more credibility than they would otherwise have, as well as a 'credibility deficit', meaning they receive less. *Hermeneutical injustice* explains that because of less participation in the practices that generate social meaning, the social experiences of certain groups remain poorly understood, even by themselves. This means that they appear not to have an adequate grip on the content they wish to convey and cannot articulate this experience to the people whose experience is the norm (e.g. scientists, legislators). For instance, this is seen in the routine reinterpretation of community concerns as 'social' rather than technical, and the struggles of communities to communicate the impact of short-term air pollution 'blasts' that are not compatible with experts' frameworks of chronic and acute exposures (Ottinger, 2010).

Epistemic justice is the principal form of EJ that I look at within my thesis, as I look at my own role in making the air visible. Through the thesis I show the way I (as an air quality scientist) produce the air in different contexts. However, in this section of the literature review I focus on my production of the air as a part of Paper 3 specifically, which was a citizen science project. I do so because the dynamics and tensions in the production of knowledge about the air are most explicit here, particularly in relation to calls for further epistemic justice. This includes what relations and legitimisation processes are embedded within different forms of air quality citizen science, and the impacts on addressing air inequalities. In the next section of the literature review I will first introduce citizen science as a mode of participatory research in air quality science, before looking at its implications for questions of epistemic justice.

2.3.1. Citizen science

Recent years have seen great effort to re-establish who is a legitimate practitioner of science, reframing the roles that the general public can play, from a 'deficit model' where the public are waiting to be enlightened by scientists who pass down their knowledge (Wynne, 2006), to being active participants in the scientific process.

Attempts to embed participatory practices into research have come under many names; Table 2.1 provides some examples of these.[14]

Table 2.1: Typologies for participatory practices in science

Terminology	Sources
Popular epidemiology	Brown (1992, 1993)
Street science	Corburn (2005)
Community based participatory research (CBPR)	Minkler (2010), Brown et al. (2012), Allen (2018)
Civic science	Fortun and Fortun (2005)
Citizen science	Irwin (1995), Bonney (1996)

While these terminologies do not perfectly map onto each other,[15] they do all aim to include citizens in the practice of science. In this thesis I use the terminology citizen science (CS) to denote public participation in research, as it is the most widely used across multiple different sectors of society. CS as a concept of professional scientific engagement with citizens has a fractured origin story having been coined simultaneously in the UK and the US. In the UK, Irwin (1995) outlined his view of CS as a science that both assists the needs and concerns of citizens, and that is developed and enacted by citizens themselves. On the other hand, in the US, Bonney's (1996) CS is a science where non-scientists can voluntarily contribute data to scientific projects. This situates the production of scientific knowledge outside of scientific institutions but it mostly follows the norms and values of science (Strasser et al., 2019). Eitzel et al. (2017: 6) characterise the main differences between the two approaches succinctly:

[14] There are interesting discussions on the similarities and dissimilarities between these different typologies of participatory research (see Reed, 2008; Schrögel & Kolleck, 2019).

[15] For a more detailed discussion on these terminologies see Eitzel et al. (2017) and Strasser et al. (2019).

> *"The first strand, from Irwin's definition, emphasizes the responsibility of science to society, which they call 'democratic' citizen science […] the second strand, 'participatory' citizen science, as practice in which people mostly contribute observations or efforts to the scientific enterprise."*

These multiple definitions might help to explain the breadth and variety of CS project goals and outcomes. It has been argued that the divergence between Irwin and Bonney's definitions is not necessarily a useful dichotomy, since in the practice of CS the terms are conflated often enough to have had enormous influences on each other and lead to projects that have goals that are synthesis of the two threads (Riesch and Potter, 2014). However, I argue that this distinction is important as at their core they offer very different epistemological visions for what CS can and should represent.

The wealth of different types of CS projects has led to institutional calls for an overarching definition of what does — and does not — constitute CS. This is principally to attempt to enshrine a minimum set of quality criteria on CS projects, and to promote more effective sharing of results and methods (see Heigl et al., 2019). However, some practitioners working in CS argue that attempts to formally define CS are "antithetical to the creativity, innovation, and bottom-up pathways to knowledge generation that are embodied by citizen science" (Auerbach et al., 2019: 15336). Pointing to previous attempts to define CS which were later shown to not fully encompass the field, Schrögel & Kolleck (2019) argue that instead of focusing on specific criteria we should instead focus on advocating for approaches that foster collaboration amongst all stakeholders for their own unique contexts. I write about CS and its compatibility with a CAQS approach in Paper 3. Including how it relates to the often-heralded main benefits of CS: democratising science, improving scientific literacy, and providing new scientific breakthroughs (Strasser et al., 2019).

Despite the increasing number of CS projects, claims of environmental injustice related to air pollution have not decreased. Indeed, further participatory research has led to new claims and strands of EJ. It is to this that I now turn.

2.3.2. Air quality citizen science and epistemic justice

Projects related to air quality have been a core part of the CS movement (see Ward et al., 2022). This relates to both institutional integration and advocacy (e.g. EEA, 2019; USEPA, 2022), and community concerns; regarding health risks, particularly for asthma, cardiovascular diseases, and cancer (Barrett, 2010; Brown et al., 2006; Chin et al., 2014; Fuller et al., 2013; Yip et al., 2004); of living near mobile (traffic) or point sources (industry) (Brody et al., 2009; Kondo et al., 2014; Svendsen et al., 2014; Wing et al., 2008); and of living in unmonitored areas (Buonocore et al., 2009; DeForest Hauser et al., 2015). These projects come in a variety of forms, fundamentally underpinned – consciously or unconsciously – by the divergent origins of CS. In my view, many more air quality CS projects follow the Bonney (1996) conception of CS.

Air quality CS has been caught up in a wider societal shift in technologies for measuring air pollution from “government-led scientific monitoring and global-scale computer models towards participatory (citizen science) modes of data collection and analysis using simple diffusion tubes and mobile phone apps” (Kenis and Loopmans, 2022: 563). Air quality CS is often framed “as a ‘tool’ to enhance public understanding of air pollution by engaging communities and local stakeholders” (Mahajan et al., 2020: 1). This has principally come in the form of air quality monitoring (Ward et al., 2022). One of the main methods of doing this has been for air quality CS projects to use low-cost air quality sensors. This has been framed somewhat as a ‘silver bullet’ to solve the democratic deficit in air quality science, and address environmental injustices (distributional, procedural, and recognition).[16] It is envisaged that through citizens being able to generate their own air quality data they can fill these ‘knowledge gaps’ and raise awareness of potential problems in their own backyards: this, of course, relies on a linear relationship between “better information and better decisions” (Ottinger, 2017c: 359).

Some question whether CS necessarily leads to EJ at all (e.g. Bidwell, 2009; Davies and Mah, 2020), as the varying models of citizen science “may either challenge or

[16] So much so that the EU’s Joint Research Centre led a workshop on this topic. See Schade et al. (2019) for a more detailed discussion on the opportunities and challenges for low-cost air quality sensing for public authorities and citizen science initiatives.

reinforce existing knowledge paradigms and interrelated power dynamics" (Tubridy et al., 2022: 622). That includes the focus on the data provided by low-cost air quality sensors which may simply lead to a "data treadmill" which both "perpetuates a narrative that effective action requires more precise data and […] resolves questions of responsibility through localised and individualised approaches to environmental pollution" (Hesse et al., 2023: 606). Moreover, low-cost air quality sensors cannot simply be considered as tools for providing the 'truth' about air pollution in a domicile. Indeed, they may even complicate discussions on what constitutes air pollution (Pritchard et al., 2018). Furthermore, this individualisation of air pollution has been argued to be "linked to neoliberal imperatives to individualise responsibility for the management of environmental problems" (Tubridy et al., 2022: 625). A point I pick up in Paper 3 where I interrogate tensions between behavioural vs structural initiatives to reduce exposure to air pollution, and ultimately improve air quality.

More fundamentally it raises foundational epistemological dilemmas about the different conclusions that can be drawn from the same air quality data, and how this data can and should be used. Some of the risk perception work (as shown earlier in the Literature Review chapter) shows how perception of risk plays a key role in how evidence of harm is created and demonstrated, and that people have an understanding of air pollution that incorporates socio-cultural factors that goes further than just "the narrower framing associated with scientific quantification" (Bickerstaff, 2004: 835). This means that even when citizens and scientists share a common infrastructure for making health assessments about potential health effects of exposure to air pollution (for example low-cost sensor networks), citizens can make meaning in significantly different ways to scientists (Ottinger, 2009, 2010; Ottinger and Sarantschin, 2017). Ottinger (2010) exemplifies this disparity through a case study in Louisiana where fence line air quality monitors were set up and shared between scientists, regulators, and community organisations. Despite this shared infrastructure the fence line monitors actually perpetuated epistemic divisions: scientists and regulatory agencies interpreted data in the contexts of regulation and problem-solving, residents interpreted data in the context of systemic danger (Ottinger, 2009). In doing so, the citizens challenged fundamental assumptions, especially distinctions between short- and long-term exposures (Ottinger and Sarantschin, 2017).

This difference constitutes a significant tension about how citizens make their data meaningful to those who they are wishing to influence. Particularly as citizen scientists are often contesting political decisions and wish to use data to influence decision-making processes. In environmental disputes, the technoscientific apparatus represents some barriers for citizen involvement. Firstly, technical experts are given a central role in environmental disputes, and these technical framings often make it difficult for communities who are not equipped with the technical jargon to meaningfully participate (e.g. Cole and Foster, 2001). Secondly, for experts, standards and standardized procedures are a ready-made way to define what data is relevant for determining safe air quality. These standards and standardized procedures provide a *boundary-policing*[17] function that allow experts to dismiss citizen generated data as irrelevant to the central project of air quality assessment given that they are often contesting the relevance of the standards for producing their claims (Ottinger, 2010). This raises a significant tension as citizens understanding and mobilisation of air quality data are often challenging experts' categories (for example short vs long-term exposure) and building on knowledges that are not formally recognised as relevant in the court of environmental disputes. This represents a form of double bind where citizens are simultaneously challenging the scientific status quo while also having to use elements of it to make their claims heard: a classic Catch-22 which I raise in Paper 3.

Making scientific collaboration with citizens 'meaningful' is an important part of EJ activism and scholarship and has manifested itself in wider calls for CS to support transformative rather than affirmative remedies for environmental injustices (Temper and Del Bene, 2016). Indeed, there have been many instances where residents have formed alliances with scientists and experts to speak out about exposures to poor air quality (Allen, 2018; Gabrys, 2017; Gabrys, Pritchard, and Barratt, 2016; Ottinger, 2010). Scientists play an important role in helping to make citizens views and ways of knowing heard, and can play the role of an honest broker with the "continuing problem

[17] Boundary policing is using recognised standards and standardized procedures to establish the authority of scientists and other technical experts, and to demarcate the boundaries between science and nonscience. See Ottinger (2010).

of epistemic injustice and the need for expert help in inventing modes of making data meaningful that are faithful to residents' experience" (Ottinger, 2017a: 47). To a great extent, scientists can define whether a project is transformative or affirmative. In the process, scientists will bring in their own knowledge and expertise, and help activists voices to be heard in the process. Residents' experiences often challenge experts' knowledge and ways of knowing, including in risk assessments (e.g. Brown et al., 2006), and calculations of statistical significance (e.g. Brown, 1992). This is not necessarily to say that these tools are wrong, but, for example in the case of risk assessments, they, by definition, are only about known possible consequences to those conducting the assessments and will exclude outside knowledge (Welsh and Wynne, 2013).

This challenge inevitably leads to some significant tensions arising between scientific rigour and bottom-up approaches (Temper and Del Bene, 2016), and raises some interesting questions, such as what the role scientific expertise should be when local knowledge and alternative ways of knowing are true errors, even within the context of their culturally specific ways of knowing. Ottinger (2017b) argues that STS scholars have yet to tackle this issue, despite it being important to quash claims of extreme relativism that might hamper activist claims in the public domain (Latour, 1999). This could leave EJ scholars and activists without the ability to advocate for the most relevant and appropriate expertise in political processes (see Collins & Evans, 2002).

Most air quality CS projects are helping to address testimonial injustices by giving marginalized voices low-cost sensors and quantitative data to bolster their credibility when they engage with experts who normally might dismiss their views. However, the progresses in solving testimonial injustice has made the hermeneutical injustices all the more visible (Ottinger, 2017a), as citizens make meaning of their data drawing upon a variety of socio-cultural factors (Altman et al., 2008; Bickerstaff, 2004; Ottinger, 2009). This means that even when citizens and scientists share a common infrastructure for making health assessments about potential health effects of exposure to air pollution, citizens can make meaning in significantly different ways to scientists. For this reason, citizens are often primarily fighting epistemic injustices: citizen scientists go against the scientific hegemony by asking different questions, giving importance to different factors, and asking for different standards of proof. CS is as much a sense-making exercise as it a data-making exercise (Ottinger, 2017a), and elements of the technoscientific apparatus (standards, instruments etc.) can help or hinder the effectiveness of CS projects. CS projects have to think strategically about which parts of the technoscientific apparatus to co-opt and which to challenge (Ottinger, 2010). This double-bind, where citizens are simultaneously challenging the scientific status quo while also having to use elements of it to make their claims heard, represents a hermeneutical injustice. Scientists play a key role in helping citizen scientists to translate their views in policy and practice. This inevitably leads to some significant tensions arising between scientific rigour and bottom-up approaches. Further investigation into these epistemological tensions between activists and scientists in the development of research methodologies, interpretation of data, and output of the results would be useful. Therefore, I pick up on these points specifically in Paper 3.

2.4. Summary

In this chapter I have outlined the groundings of some of the specific contributions in each of the papers and the wider contributions of the thesis. First, I outlined the critical physical geography (CPG) literature, detailing its genealogy and practice. I did so because it fundamentally underpins one of the main contributions of this thesis: the development of a critical air quality science (CAQS) framework to study air pollution's sociomateriality (Paper 3). While I do not claim for CAQS to simply be CPG transposed to air quality, if it is taken in that way, I hope that my thoughts from CAQS can be transposed straight back to CPG to bring air quality more fully within the scope of CPG. Second, I looked at the bifurcated social and natural study of air quality. I outlined how I contribute to previous work, investigating the role of air quality scientists and their instruments in producing the air through drawing upon my multiple and shifting identities across different types of science. I then outlined how I contribute to hybrid ways of doing air quality science (both in general, and in particular for indoor air quality), principally drawing on (and expanding upon) the work of Cupples (2009). Third, through treating air quality as a hybrid phenomenon, I carefully considered how to theorize cases of EJ and what ethical obligations surround it (Ottinger, 2017b). The result culminated in epistemic justice as the most relevant form of justice for understanding the effects of my own role in mediating what comes to count as air pollution, how it is represented, and who it benefits: especially related to citizen science.

3. Methodology: Studying the doing of air quality science

In this thesis I deploy several different social and natural science methods, including air quality monitoring, actor-network theory (ANT), 'near' ANT, semi structured interviews, and varying forms of ethnography. Some of these methods are deployed across the thesis, whereas others are deployed in individual papers. While the individual papers are self-contained and detail the methods deployed, in this section I outline their underpinnings. I start with a brief historical overview of developments in science and technology studies (STS), before introducing the main methodological influences on my thesis.

3.1. Studying scientific practices

There is a long history of subjecting science to the sociological gaze, especially looking at the practice of science. Thomas Kuhn's *The Structure of Scientific Revolutions* (1962) challenged the dominant view of the history of science, arguing that the history of scientific discoveries should not be told as a story of uninterrupted progress; rather, it should be told merely as a story of change. Kuhn shifted the focus of the results of science being an inevitable accumulation of knowledge to instead look at the *practice* of scientific research. In other words, he began to understand scientific practice in local terms rather than the macro-level of scientific progress.

Following on from this, the sociology of scientific knowledge (SSK) framework sought to shine a light on scientific endeavours to show how scientific 'facts' are made, to emphasize that science is social at its core, and that scientific knowledge has to be understood "not as the transparent representation of nature, but rather as knowledge relative to a particular culture, with this relativity specified through a sociological concept of interest" (Pickering, 1993: 5). The SSK movement, underpinned by *the Strong Programme* (Bloor, 1976; Barnes and Bloor, 1997; Shapin, 1975) was committed to an empirical and naturalistic approach to studying scientific knowledge. This meant that studying how scientific knowledge was social should be examined through studies of real science (Pickering, 1993), emphasizing a structure of symmetry: beliefs judged true and false, or rational and irrational should be explained using the same methods since there is no rational guaranteed path from the material world to a scientific truth, and by themselves, truth, rationality, and the material world have limited value in explaining why one scientific claim is believed over another (Sismondo, 2010). It's most concise statement is outlined in David Bloor's (1976) four tenets of causality, impartiality, symmetry, and reflexivity.

However, it is the approaches that came from the 'practice turn' in the studies of science that began to appear in the late 1970s from where I draw most inspiration in this thesis. These approaches had similar concerns to SSK (e.g. rejecting philosophical apriorism and studying the content of science and technology in social terms), but attempted to shift the research focus from the *products* of science (e.g. knowledge), to the *practice* of science: that is, what scientists actually do. Where SSK focused on scientific culture as a single conceptual network (as did Kuhn with the concepts of paradigms), science as practice embraced the messiness of doing science, with its materials (scientific instruments, and the objects observed), ideas (theories, questions, and hypotheses), and marks (data, calculations, and interpretation) being made and re-made into a scientific culture (Hacking, 1992). This multiplicity of the technical culture of science where any number of things beyond interests can explain how scientific facts are made highlighted the importance of scientists in bringing together (and adjusting) materials, ideas, and marks. For the practice turn, ethnography was the main tool to study what scientists actually do. I will now turn to ethnography as the first distinctive methodological underpinning of this thesis.

3.2. Ethnography

Ethnography is the "first-hand experience and exploration of a particular social or cultural setting on the basis of (though not exclusively by) participant observation" (Atkinson et al., 2007: 4). Ethnography has moved far beyond its – problematic – roots of the anthropological study of remote tribes by a lone ethnographer. It has since been used as a research tool and method in a wide range of disciplines, including (but not limited to), anthropology, human geography, sociology, medical science, educational research, and STS. In this thesis, I largely build off its uses in STS. In STS, ethnography has been the main methodological tool deployed to study the practice of science, allowing researchers to “see the relative messiness of practice” and to look “behind the official accounts of method (which are often clean and reassuring) to try to understand the ragged ways in which knowledge is produced in research” (Law 2004: 18–19).

Atkinson et al. (2007) argue that heuristically the methods and theoretical frameworks deployed for ethnography in STS can be split in to two generations. In the first generation, the laboratory became a site of ethnographic observation as STS scholars sought to understand how the laboratory made facts and could give stability and strength to claims. Treating scientists as ‘alien’ allowed ethnographers to follow them through society, none more famously than Latour and Woolgar in *Laboratory Life* (1979)*,* who showed how the daily practices of scientists in their laboratory created the scientific fact of the peptide TRF(H)*.* The second generation of ethnography in STS “tended to be more oriented towards social problems (environmental, class, race, sex, sexuality, and colonial) in addition to theoretical problems in the sociology and philosophy of knowledge” (Hammersley and Atkinson, 2007: 236). This opened a space to examine not just experts, but also lay people, activists, and the media, facilitating a stronger focus on notions of culture and power.

The revelatory nature of my PhD that changed its direction whilst in the process of doing air quality science somewhat confounds my attempt to give a more ‘standard’ account of my choices of method: I chose *x* method, which consists of *y*, to help me uncover *z*. Indeed, my original methods were very much dictated by the logics of air quality science, including where to place air quality monitoring equipment to measure the air most representatively, how to keep air quality monitors running reliably, and methods to analyse the data: these sorts of methods are presented and interrogated in Paper 1. I could have carried on doing an air quality science PhD based on these methods to look at the air’s relation to questions of distributive environmental justice. However, upon discovering my own role in constructing the air through deeper engagement with STS and related literatures, it seemed illegitimate to obfuscate my situated and partial positionality. As such, new methods were required to allow me to investigate my own mediating role in the way the projects were set up, how results were represented, and the effects of these mediations (and on whom). This change in direction led me towards ethnographic methods: in particular, relational and reflexive ethnographies. My account of my use of these methods would be insincere if I claimed that I consciously mobilised these concepts from the start of the PhD. Moreover, if I was to do so it would contradict the very nature of me coming to realise my own mediating role in the representation of the air. Instead, I include information on relational and reflexive ethnographies as this is where I feel that my research now sits. In the following section I will introduce the concepts of reflexive and relational ethnographies and explain how my research draws upon and contributes to them. I will detail the different ways that it does so across the papers that form this thesis. It is also worth noting that there are significant overlaps between reflexive and relational ethnographies, including on their use of reflexivity as a tool. However, there are some important distinctions between them which, at least in my view, renders a combination of them more apt.

3.2.1. Reflexive ethnography

Aull Davies (2012: 4) argues for a "reflexive ethnography", that as well as conducting research in line with a more traditional ethnographic method, also studies how "the products of research are affected by the personnel and process of doing research." This includes the "who, what, when, where, and how to research, decisions necessarily tied to institutional requirements (e.g. Institutional Review Boards), resources (e.g. funding), and personal circumstance […] " (Ellis et al., 2011: 274). I use reflexive ethnography across the thesis as a method to look at my personal circumstance in the doing of science. Of course any research that centres the researcher is vulnerable to claims that it tells "us about the ethnographer, not about the social and cultural phenomena that are the proper subject matter of ethnography" (Aull Davies, 2012: 179). However, by using reflexive ethnography to show not only how my personal history "but also the disciplinary and broader sociocultural circumstances […] have a profound effect on which topics […] are selected for study" (Aull Davies, 2012: 5) I aim to speak of the "epistemic culture" (Knorr-Cetina, 1981) of air quality science: a culture that I am embedded within and that Cupples (2009: 209) argues “appears to disable the possibility of incorporating alternative knowledges and cultural insights into research.”

While I do draw on the concept across all the papers (or at least this is where it now fits), I do not explicitly use the phrase in all of them. In Paper 1, I do reflexive ethnography through interrogating my role that broadly fits within two identities: 1) as a PhD researcher at Lancaster University, and 2) as the CEO of NAQTS, the company that makes the air quality monitoring equipment that I used in this PhD. I outline these identities in more detail in Paper 1, where I use the term ‘autoethnography’: an approach to research and writing that uses tenets of autobiography and ethnography to “describe and systematically analyze (graphy) personal experience (auto) in order to understand cultural experience (ethno)” (Ellis et al., 2011: 273). By drawing on my past experiences of doing air quality science I mobilise these two identities as a “convenient tool for […] indicating choices made by the author” and to display “ways in which points made can be misleading” (Sismondo, 2010: 154). Indeed, I appreciate that in Paper 1 there appears to be a tension in the fact that in one thread I establish a set of facts of ready made science, and in the other, by showing the construction of the fact, I appear to delegitimate the former (Sismondo, 2010). However, Aull Davies (2012: 189) aptly highlights the strength of taking an approach where my ethnographic self somewhat ‘others’ my other self:

> *“It is precisely in this process of interaction between ethnographer as self and ethnographer as other that social knowledge of general interest and significance is produced. The interaction of the ethnographer-as-researcher, informed by the theoretical positions of other social research and in a dialogue with a social scientific community, with the ethnographer-as-informant, with access to the knowledge and experience of an insider, differs in degree but not in kind to other manifestations of the research relationship through which generalizable knowledge about social and cultural realities is produced.”*

In Paper 2, I directly use the phrase reflexive ethnography to explain how I both draw upon my own direct involvement in the project, as well as other internal project documents, to show the ways that the research was affected by the researchers carrying it out. By looking at how the doing of science changed upon the emergence of COVID-19, I made visible the decisions over what coefficients were used to represent the infectivity of the virus, and the overall project shift from characterising the air to improving it. In Paper 3, I did not directly use the phrase reflexive ethnography. However, through opening up my own role in air quality citizen science knowledge production, including tensions between my ‘formal’ knowledge and their ‘informal’ knowledges I brought a strong reflexive element to my research. Moreover, I also included reflexivity as part of a new critical air quality science (CAQS) framework that I developed in the paper, a tenet of research that I hope “can represent professional practice more fully and bring about ethical action” (Denshire, 2014: 845–846), especially related to goals of epistemic justice.

3.2.2. Relational ethnography

Relational concerns are also a crucial dimension of ethnographic inquiry (Ellis et al., 2011). Therefore, as well as drawing upon reflexive ethnographies, I also draw upon the concept of relational ethnography which “takes as its object configurations of connections, transactions, and unfolding relations” (Desmond, 2014: 574). The aim of relational ethnography is to give “ontological primacy, not to groups or places, but to configurations of relations” (Desmond, 2014: 554). I use relational ethnography in three ways: first to talk about the construction of my object of study; second to talk about the process of research translation; and third to provide a sociomaterial ethnographic account.

Using relational ethnography to talk about the construction of my object of study is focused on “studying fields rather than places” and “boundaries rather than bounded groups” (Desmond, 2014: 574). By studying fields rather than place, I do not “amputate social relations through the imposition of categories based on bounded places” (Desmond, 2014: 563). Instead, I attempt “to reconstruct a network of relations that guide everyday life” (Desmond, 2014: 563), which can transgress the immediate place of study. For example, when I deploy relational ethnographic methods across this thesis to analyse the practices that constitute air quality science, I do not take the specific place as the unit of analysis, whether that be a school in Lancaster, or a community in Liverpool. Instead, I look at the relations in these localities that can span different scales. This includes, for example, local and national government, national metrological institutes, and the role of Lancaster University. By studying boundaries rather than bounded groups, I focus on "'group-making' and 'grouping' activities such as classification, categorization, and identification" (Brubaker et al., 2004: 45), rather than a single group's actions and beliefs per se. I do so to not essentialise a group based on a single category (for example sex, race, or class), but instead to look at the intersection of multiple categories that they are embroiled in. For example, in Paper 3, I do not take the residents of community group Better Old Swan to be representative of a single social characteristic, whether that be Liverpudlians, inner-city residents, purveyors or lay knowledge, 'insiders', or any other group designation. Instead, I focus on the relations between themselves and me, looking at, for example, epistemic boundaries in the interpretation and use of air quality data to construct claims of harm. In doing so, I see social locations as shifting and permeable, rather than fixed and static (Naples, 1996).

Second, I use relational ethnography as an approach to make visible the processes and relations wrapped up in doing research. I use it as an approach "which embraces reflexivity, responsivity, transparency of the researcher(s), relational awareness and dialogical coherence between that which is being researched and how research material is shared with others" (Simon, 2013: 11). I do so by "speaking reflexively and dialogically about and from within relationships" (Simon, 2013: 11). There are some significant overlaps between the focuses of reflexive ethnography and this strand of relational ethnography. However, in this instance relational ethnography extends the principle of reflexivity beyond that of individual experience into explaining how "the shaping of my research endeavour and its telling will be influenced by many others, directly and indirectly involved with it" (Simon, 2013: 11). In Paper 1, I use this approach to speak reflexively "from within the different voices of the researcher's inner dialogue" (Simon, 2013: 11) as I contrast my voice during science in the making vs ready made science. By doing this, I hope to "invite others into a privileged and otherwise unexposed view of the inner and outer workings in the life of a practitioner" (Simon 2013, 10). In Paper 2 and Paper 3, through both looking at how the doing of science was adapted to deal with the emergence of COVID-19, and in my interactions with citizen scientists, I use relational ethnography as an approach that focuses on "what counts as knowledge; how, with and for whom "knowledge" is produced and with what social consequences” (Simon, 2013: 11). In Paper 2 this comes under the guise of ‘matters of care’ (Puig de la Bellacasa, 2011), a term used to advocate for approaches that take responsibility, do care, and think ethically and politically about how “ways of studying and representing things can have world-making effects” (Puig de la Bellacasa, 2011: 86). I do this in Paper 2 by illustrating how the project changed from ‘neutrally’ observing and gathering evidence on poor indoor air quality (IAQ), to instead focus on intervening to improve IAQ and mitigate COVID-19. In Paper 3 I do this through highlighting tensions in the production of knowledge about the air showing the relations at work in evidencing potential harm. Moreover, through developing a CAQS framework, I outline ways to productively investigate the air, including its materiality, social dynamics, and implications on knowledge politics.

Third, I do a relational ethnography through using a sociomaterial perspective to highlight the role of non-humans in the construction of our social worlds. In a sense this is simply using the two relational approaches mentioned beforehand but from a relationally ontological perspective that brings non-humans into my accounts. In particular I use ANT as a sociomaterial approach, and as such I call myself an “actor-network theory informed ethnographer” (MacLeod et al., 2019: 180). In the following section I will explain what ANT is, and my use of it in more detail. Although in brief, I use ANT in Paper 1 to highlight the role of the air quality monitor that I use (and that I developed through my company), and the air pollutant measured in constructing a certain understanding of the air. In Paper 2 I use ANT to look at the effect of different documents on “what and how humans interact with their environment” (MacLeod et al., 2019: 181), in particular, on designating indoor spaces as breathable and enacting practices of ventilation.

Of course, none of this is to say that ethnographic methods in general do not have their perceived shortcomings. However, rather than focus on well-rehearsed arguments for and against different modes of ethnography (e.g. Lynch, 2000; Hammersley, 2006), I highlight a few specific challenges I encountered. First, and perhaps most obvious, given the revelatory nature of the PhD, and the shift from the *doing of* air quality science to the doing and *science of doing*, I was not armed with a note pad and pen from the start of my research, the main equipment of the ethnographer (Bryman, 2008). As such, my field notes were lacking, and I was more reliant on internal communications (such as emails), external documents, and my own memory to help construct the accounts of which I describe. Of course this is not a completely alien practice to ethnography, as for autoethnography the author often "retroactively and selectively writes about past experiences" that they did "not live through […] solely to make them part of a published document" (Ellis et al., 2011: 275). Indeed, more than anything this highlights "the improvisational nature of ethnographic fieldwork" which "stands in contrast to the formulaic quality usually associated with the concept of methods" (Cerwonka and Malkki, 2008: 22). The second challenge was about knowing my positionality, or where I am speaking from at different points. This was a particular challenge given the multiple identities that I bring to the fore in this thesis. Knowing how to separate my ethnographic self from my other self was difficult (and perhaps even arbitrary), particularly in an age of increased research-business collaboration where lines are somewhat blurred. However, throughout doing this PhD my identities hung together well enough that it made sense to use the labels, but not well enough that they were single, or did not shift.

3.3. More than human air quality: Actor-Network Theory

One of the implications of seeing the "relative messiness of practice" (Law, 2004: 18) is "discovering that human and non-human actors are entangled in complex ways" (Garnett, 2015: 63). The more-than-human and new materialist shift in the social sciences has shifted social theorizing "from epistemology to ontology" leading to "the recognition of matter's intrinsic activity" (Gamble et al., 2019: 118). This began as a fairly novel, or even controversial contribution across the social sciences. However, nowadays, it is clear that "nonhumans are no longer missing" (Sayes, 2014: 135) in social science accounts.

In this thesis I use ANT, perhaps the most widely used concept to illustrate the shift of focus from the macro-level forces (such as structures and institutions), and to instead focus on the micro, including the practices of scientists and their instruments, and the roles of non-humans. Originally developed by Bruno Latour (1988), Michel Callon (1984), and John Law (1984), ANT is a *material-semiotic* framework that states technoscience to be the making and (re)making of networks of human and non-human actants. Latour (2005: 5) describes ANT as an attempt to redefine sociology "not as the “science of the social”, but as the “tracing of associations”” (Latour, 2005: 5). Latour asserts that sociologists should be accounting for how society is held together rather than using a notion of ‘the social’ to explain phenomena. In brief, ANT argues that humans and non-humans have interests that cause them to act, and they form associations to establish networks. The work of technoscience is to translate the interest of actants so that they can work in agreement. Actants build networks, whether that is components of a machine that allow it to function or turning beliefs into scientific facts.

I use ANT as a mode of enquiry to “attend closely to the rich array of the senses, dispositions, capabilities and potentialities of all manner of social objects and forces assembled through, and involved in, the co-fabrication of socio-material worlds” (Whatmore, 2006, 604). Indeed, ANT has investigated the role of a huge number of non-humans, including:

> “entities as diverse as animals (such as scallops – Callon, 1986), natural phenomena (such as reefs – Law, 1987), tools and technical artifacts (such as mass spectrometers – Latour and Woolgar, 1986 [1979]), material structures (such as sewerage networks – Latour and Hermant, 1998), transportation devices (such as planes – Law and Callon, 1992), texts (such as scientific accounts – Callon et al. 1986), and economic goods (such as commodities – Callon, 1999)” (Sayes, 2014: 136).

ANT has been used as a framework for an enormous number of studies, in a wide range of fields, including in the discipline of geography and its subdisciplines (e.g. Allen, 2011; Ruming, 2009; Müller, 2015; Bickerstaff, and Agyeman 2009; Holifield, 2009). This also includes those within geography looking at air quality per se (e.g. Cupples, 2009; Whitehead, 2009; Garnett, 2015). This widespread use, and the benefits it has conferred for various scholars is to not to say that ANT is without drawbacks, or criticisms. In fact, the critiques of ANT are numerous and well-rehearsed. Sismondo (2010) summarises these broadly into four categories: *practices and cultures* – ANT negates the context of existing technoscientific practices and cultures which foregrounds how decisions are made; *problems of agency* – particularly

ANT's treatment of non-human agency;[18] *problems of realism* – ANT's flat ontology means that natural objects cannot be said to have any real scientific properties or technical properties to do anything until they are enrolled into a network;[19] and *problems of the stability of objects and actions* – ANT accounts for scientific objects and facts as powerful because of the rigidity of their translations, but rigidity of translation may be a fiction hiding multiple layers of expert judgment, tinkering, and tacit knowledge. Likewise, Lave (2015: 221) argues that it is "time to retire ANT as a core element of the political ecology tool kit"[20] due to its categorical denial of structural inequalities, uncertain political implications of dealing with humans and nonhumans symmetrically, and the neoliberal conceptualisation of its actants. In truth, whether one sees ANT as a useful tool for embracing a hybrid world, or a politically useless game of "epistemological chicken" (Collins and Yearley, 1992a) appears irreconcilable. Nonetheless, I find ANT to be a productive tool for three main reasons.

First, I find ANT a "coherent methodology for incorporating nonhumans into social scientific accounts" (Sayes, 2014: 135). Of course, this depends on one's view on non-humans. However, for me, as Latour (2005: 225) argues "it is when power is exerted through things that don't sleep and associations that don't break down that it can last longer and expand further – and for this, of course, links made of another social contract are required." Indeed, learning the language to allow the V2000 – and other non-humans – to 'speak' back to me was one of the main things which led to my change of direction in this thesis, as I could see the work that my air quality monitor was doing to embed a very particular relation with the air.

Second, I find ANT's flexibility and wide range of concepts attractive. In Paper 1, I both use ANT in a more a traditional form (e.g. Latour and Woolgar, 1979) to show my construction of the air by contrasting science in the making with ready made science,

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[18] See Collins & Yearley (1992a) and Callon & Latour (1992) for an exchange on the value of including non-humans in sociological accounts.

[19] Collins & Yearley (1992a) provide the most famous rebuttal to this, stating that ANT's implicit realism, as made clear in Latour's *Science in Action* (Latour, 1987), shows how some facts are so concrete, and made so strong in their networks, that one can longer doubt their existence.

[20] There are many overlaps between political ecology and geography in this domain when dealing with nature-society relations.

but also incorporate the concept of ‘circulating reference’ (Latour, 1999) to show how my representations of the air could go back to their original matter in a series of transformations. In Paper 2, I position myself as working ‘near’ ANT (Farías et al., 2020), a term I use to designate both a close relationship with ANT but also with other more-than-human approaches. From ANT, I borrow some specific concepts that have been widely used in the social sciences, such as immutable mobiles, and centres of calculation (Lave, 2015). I combine these concepts with others that run alongside ANT, for example, ‘matter of care’ (Puig de la Bellacasa, 2011). I also position the paper as ‘near’ ANT, rather than ‘all-in’, to differentiate myself from the ‘after’ (Law, 1999) and ‘post’ (Gad and Jensen, 2010) ANT debates. I do this to avoid the potential dichotomous stabilisation of what ANT was, and subsequently should be that can be found in these debates around certain key concepts (Farías et al., 2020).

Third, I find ANT as an interesting alternative way of conceptualising inequality. In response to one of the principal critiques of ANT of it not being politically useful (Collins and Yearley, 1992a; Lave, 2015), I find ANT a useful tool to think of inequality “not as great structures but as relatively non-coherent enactments which nevertheless resonate or interfere with one another to keep each other in place” (Law, 2004: 141). Indeed ANT has been used as a critical approach to trace the things that constitute and scale environmental justice (EJ) (e.g. Bickerstaff and Agyeman, 2009; Holifield, 2009). For example, in Paper 2 I speculate on how the enrolment of hundreds of thousands of new carbon dioxide (CO_2) IAQ monitors to manage COVID-19 will change air pollution exposures for different classrooms around the UK. By using CO_2 as a proxy for IAQ, the aim is to reduce its concentrations by promoting ventilation, bringing in more outdoor air which itself may itself be polluted. This has problems for questions of EJ as outdoor air pollution is not evenly spread. Moreover, through focusing on the agency of the CO_2 sensor, I highlight how it reinforces IAQ as a matter of ‘personal care’ (Whitehead, 2009), that is not the responsibility of the government: even if, for example, illegal concentrations of traffic air pollution from outdoors have wafted in through an open window.

Of course, none of this is to say that using ANT is a cakewalk. Indeed, it did present a few specific challenges. First, ANT’s huge arsenal of concepts was both a challenge as well as an opportunity: knowing which of its concepts to most fruitfully use without getting lost in its own self-referential scheme, or "infralanguage" (Latour, 1996) was difficult. Second, while I do find ANT's inclusion of non-human actants illuminating, by opening up the avenues for far more things to enact agency it makes choosing which actants to follow a daunting task. While Latour (2005: 258) provides some advice on what to do here by suggesting that the analyst should be "undecided as [to] the various actors we follow", it remained a difficult endeavour to know where to start. Indeed, I remain sceptical as to the possibility of truly allowing non-humans to speak for themselves, especially when during the written accounts of them it is ultimately me that allows them to speak. Third, and related to knowing where to start, is knowing where to stop. One of the potential pitfalls of ANT is that every actant is in itself in a network. Here lies the potential for an endless regression which might provide more description of a situation without necessarily saying more. In Paper 1 I attempted to deal with this problem by focusing on three main actants and their first order associations (Murdoch, 1997), to try and spend more time focused on actants that were significant across the papers that form this thesis.

3.4. Summary

In this chapter I have outlined the methodological underpinnings of my focus on studying the doing of air quality science. This focus has led me draw upon reflexive and relational ethnographies, and actor-network theory (ANT). Regarding my use of ethnographic methods, I outline how I did not explicitly use some of the terminologies in the papers, given the revelatory nature of my PhD, but how I feel that they sit within these methods.

I draw on reflexive ethnography as a method to show how the way research is done and represented is affected by both the people and process of doing research. In doing so I allude to a wider epistemic culture of air quality science. I do this in Paper 1 through using an autoethnographic approach that reflexively mobilises past experiences (and the two identities that were prevalent) of doing an air quality monitoring project. In Paper 2, I both analyse my own direct involvement in a research-business air quality monitoring project and related project documents to show how the doing of science was affected by the researchers carrying it out. In Paper 3, I develop a critical air quality science framework (CAQS) – which includes a reflexivity tenet – to reflexively analyse my role in an air quality citizen science project and outline tensions in knowledge production between myself and the citizen scientists.

I also draw on relational ethnography as a method in three main ways. First, for the construction of the object of study by focusing on fields rather than places, and boundaries rather than bounded groups. I do not take any place as the specific unit of analysis. Rather, I focus on relations in these places that can span different scales. Moreover, I don't essentialise any group based on a specific social category, but instead focus on how these groups are made. Second, to focus on research translation to make visible the practices and relations wrapped up in doing research. I do this in Paper 1 by using two narratives to compare science in the making with ready made science. In Paper 2 and Paper 3 I do this by showing how the doing of science in its more traditional form was destabilised. Third, I provide a sociomaterially relational ethnography, bringing non-humans into my accounts: in particular I use ANT. I use ANT in Paper 1 and Paper 2 of the thesis, as a coherent methodology for incorporating nonhumans into social scientific accounts, drawing on its flexibility as an alternative way of conceptualising inequality.

Given my embrace of the return to matter, ontologically I am certainly of the view "that there is a world out there and that knowledge and our other activities need to respond to its 'out-thereness'" (Law, 2004: 7): no matter how the air is socially defined it has material effects. However, at the same time, "while the 'real' is indeed 'real', it is also *made*, and that it is made within relations" (Law and Urry, 2004: 395). As Latour (1990: 71) aptly puts it, "a little bit of constructivism takes you far away from realism; a complete constructivism brings you back to it." Through using ANT I embrace a relational ontology that argues that science "participate[s] in the social world, being shaped *by* it, and simultaneously *shaping* it" (Law, 2004: 12). Moreover, given that the air is both real and constructed it is ontologically multiple (e.g. Mol, 2002), highlighting a critical role of its construction (which is largely done by the activities of science) on the ontological politics (e.g. Mol, 1999) of what worlds scientists bring into being.

4. From (Particulate) Matter to Form: Opening the black box of doing PhD air quality science (Paper 1)

Abstract

In air quality science the data are often said to speak for themselves. However, it has been shown that the 'facts' that science produces cannot be separated from the people and instruments that produce them. There have been recent calls for air quality scientists to open the black box of air quality knowledge production to investigate what relations they are embedding and legitimising, and ultimately what world(s) they are making visible. Following these calls, in this paper I autoethnographically analyse a school indoor and outdoor air quality monitoring project that I led. I contrast the difference between 'ready made science' and 'science in the making' through deploying two concurrent threads. The first thread draws upon Actor-Network Theory to investigate the human and non-human actants that influenced the questions about air quality that the research asked, and how they were investigated. I interrogate three main actants: the air pollutant that was measured, the air quality monitor that was deployed, and myself through the identities as a PhD Researcher and company CEO I performed. I also draw upon the concept of *circulating reference* to show how the final representation of the air was generated and stabilized. The second thread presents the conventional account of the doing of air quality science through a series of boxes alongside the main body of text. Through contrasting these two threads, I show how the air was made in this project, and how the conventional air quality science account is not enough to explain how and why this form of science was done.

4.1. Introduction

Science has long been presented as the rigorous pursuit of objective truth, achieved through the ordered and logical practices of scientists. The work of the laboratory studies (e.g. Knorr-Cetina, 1981; Latour & Woolgar, 1979; Traweek, 1988) challenged this depiction through ethnographically analysing the practices of scientists in their laboratories, and in the field. Through focusing on the day-to-day activities of scientists, including their uses of certain instruments and methods, the laboratory studies questioned how facts were 'made' (and made to be stable and strong), which cast a wider net of contingent influences beyond essentialist references to simply 'following the science'. Instead, it was argued that "scientific facts cannot be dis-entangled from the scientists and the instruments that produce them" (Cupples, 2009: 209). In other words, that the knowledge produced by scientists is always situated in some way (Haraway, 1988).

Numerous works have demonstrated this entanglement in air quality science (Cupples, 2009; Garnett, 2017; Whitehead, 2009). Whitehead (2009) showed how understanding and governing of the air in the UK shifted as new technologies became available that could measure the air while it was suspended, rather than once it was deposited on surfaces. Likewise, Garnett (2017) has shown how different groups of researchers had different expectations of what would come to count as 'good data' to represent air pollution based on different ways of knowing air pollution. Cupples (2009: 209), drawing on Knorr-Cetina (1981), argues that there is an epistemic culture within air quality science that renders it incapable to "simultaneously acknowledge the physicality and seriousness of air pollution, but also pay attention to the places and spaces in which air pollution (knowledge) is produced and performed." However, there have been recent calls for air quality scientists to open the black box of air quality knowledge production (Booker et al., 2023; Cupples, 2009), through taking – amongst other things – a more 'reflexive' approach to "probe why certain scientific concepts and theoretical frameworks are being used, what worlds they are making visible, [and] what relationships they are legitimising" (Booker et al., 2023: 3). This is in part because air quality scientists, and the instruments that they deploy, play a crucial role in producing our relation to air quality, which otherwise may remain elusive and unperceived. It is in this context that I challenge the ordered account of doing air quality science from an indoor and outdoor air quality monitoring project at a school in Lancaster, UK. I do so to identify key moments during the process of doing air quality science where air quality scientists mediate our understanding of the air. In doing so, I aim to identify areas of potential intervention to facilitate a more effective and equitable engagement on issues of air quality. This reflection takes on a different flavour to a traditional laboratory study ethnography in that I reflect on *my own* formal account of the air quality monitoring project that I delivered.

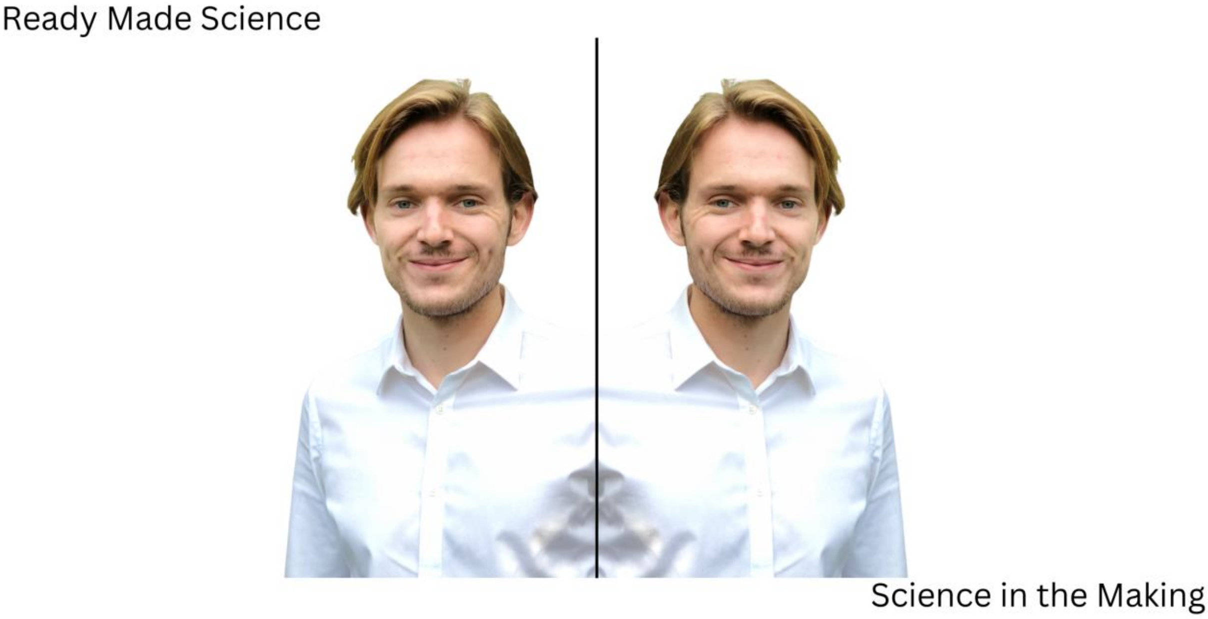

Figure 4.1: My two faces. Adapted from Latour (1987)

My reflection takes inspiration from two texts. First, I draw from Latour's (1987) *Science In Action*, which contrasts the difference between 'ready made science' and 'science in the making' depicted in the dialogue between Janus's – or in this case my – two faces, as shown in Figure 4.1. On the left side, we see ready made science: facts of the natural world that are unearthed through the authority conferred by scientific procedures. On the right side, we see science in the making: facts that are under construction. This depiction is useful as an entry-point to understanding science; not from a point of view that aims to legitimise the already stable ready made science, but instead to see how through science in the making the 'facts of the natural world' appear (De Boer et al., 2020). Second, I stylistically draw on Mol's (2002) *Body Multiple*, which juxtaposes two concurrent texts: one on her ethnographic material, looking at the day-to-day diagnosis and treatment of a specific disease, and the other discussing literature relating to the case.

I combine the approaches in these two texts to contrast science in the making against ready made science through detailing two concurrent threads. The first thread follows me through the process of doing the air quality science, drawing on auto-ethnographic material from the air quality monitoring project. By using autoethnographic material, this paper differs from the traditional ethnographic method of participant observation and analysing field notes (Atkinson et al., 2007). Instead, in this paper I evaluate the air quality monitoring project that I led *post hoc*, drawing upon Actor Network Theory (ANT), a "disparate family of material-semiotic tools, sensibilities and methods of analysis that treat everything in the social and natural worlds as a continuously generated effect of the webs of relations within which they are located" (Law, 2016: 141). A key component of the ANT corpus is that it treats all entities, human or non-human, as equal in their potential agency to configure action (Sayes, 2014). I draw upon ANT to detail the human and non-human actants[21] that had influence in determining the questions about air quality that the research asked and how they were investigated. Of course, any ANT account is merely a partial representation of what was – potentially – acting, as every actant is itself a network. To spend more time focusing on actants that take an important role across the project, I focus on three main actants and their first order associations that detail the most significant relations and actions within the networks (Murdoch, 1997): the pollutant that was measured, the air quality monitor that was deployed, and my identities (which I understand as emerging from my actor network enrolments as both the lead researcher and network translator). These actants are outlined in more detail in the sections that follow before their roles are analysed in this project.

The second thread, placed in boxes adjacent to the main body of text, details the conventional air quality science account of the doing of air quality science. I refer to these boxes as 'Ready Made Science' (RMS), and I also use a different font to clearly illustrate the different line of thinking. The RMS thread details the process of doing the air quality science following the expected procedures and norms of how such an

[21] A term used in ANT to replace 'actors' to emphasize that their action is relational.

account should be described and structured, from the justification for the research focus and design, through to the presentation of its results. For example, RMS 1 details how the air quality measurements were set up to investigate environmental justice related concepts of vulnerability and susceptibility through air quality measurements in new locations, at high temporal resolution, and of emerging air pollutants of concern. In particular, this study set out to understand when and where the air pollution exposure pathways are greatest for school children during the school day. While the factors outlined in RMS 1 are important in explaining how and why this form of scientific study was set up, I will argue that there were a wider array of human and non-human actants intertwined in the "dynamic assemblage" of this air quality research (Walker, Booker, & Young, 2022). These other actors are important because they embed a certain set of relations with the air that ultimately informs our understanding – and ultimately our making – of air pollution.

RMS 1: Study Rationale and Motivation

This study investigates indoor and outdoor air quality at a school, to investigate when and where the air pollution exposure pathways are greatest for school children during the school day. Specifically, this study focuses on air pollution in the form of ultrafine particles[22] (UFPs).

What motivates the study? Children are especially susceptible to air pollution (Adair and Arroyo, 2018) due to both their higher inhalation rates relative to body mass and narrower airway passages, which, when inflamed, have a proportionately greater airway obstruction and can exacerbate existing respiratory conditions, such as asthma (Takenoue et al., 2012). The UK has the highest per capita rates of asthma symptoms globally in children (Global Asthma Network, 2018), with substantial regional disparities in mortality rates owing to access and quality of health care and socioeconomic factors (Gupta et al., 2018). More than just exhibiting negative health consequences, exposure to air pollution has also been associated with poor academic performance among school-aged children (Mohai et al., 2011). These susceptibilities are exacerbated by a vulnerability function: children are more physically active than adults, and their inhalation occurs closer to the ground where air pollutant concentrations tend to be more concentrated (Goldizen et al., 2016).

Why measure the air quality at school? Research on air pollution has traditionally focused on outdoor, ambient air quality (AAQ), despite people in Western industrialised countries spending ~ 90% of their indoors, where concentrations for certain pollutants can be greater than outdoors (AQEG, 2022). The combination of both the length of time spent inside, and the potential for higher concentrations means that personal exposure for some air pollutants is greater indoors (Vardoulakis, 2009). Therefore, the current exposure-based assessments of likelihood of health consequences based on AAQ are not reflecting real-world patterns of

[22] I use the terms particle and aerosol interchangeably throughout this paper.

exposure. However, to understand indoor air quality (IAQ), one must rely on the principle that the indoor atmosphere is an extension of the outdoor atmosphere: outdoor air pollution does not stop at the front door. The combination of these factors means that research only looking at IAQ would not be fully engaging with the dynamics of air pollution. To understand patterns of exposure, one must have a holistic understanding of air pollution, indoors and outdoors. Combining notions of measurement location, and vulnerability and susceptibility, schools were selected as the indoor environment because children spend a significant amount of time at school: ~190 days per year, and ~30 hours per week (Long, 2019).

Why measure at high temporal resolution? Emerging evidence points towards the role of short-term exposures in acute health effects. For example, Chen et. al (2020) found that even a few hours exposure to UFPs could trigger a non-fatal heart attack. These shorter-term exposures are not routinely included in standard monitoring programs and procedures. The dropping off and picking up of school children represents a significant potential short term exposure to traffic related pollutants including UFPs (Adams and Requia, 2017).

Why measure ultrafine particles? UFPs were chosen because most knowledge on the health effects of particulate matter (PM) is related to the regulated standards of $PM_{2.5}$ and PM_{10} (Dominici et al., 2006): UFPs are unregulated in worldwide air quality standards (AQEG, 2018). Subsequently, much less has been done to understand the health effects of UFPs (in part due to lack of available UFPs data), which are small enough to translocate into the bloodstream. Toxicological studies have suggested that UFPs may be more toxic per mass unit than the regulated larger particles of $PM_{2.5}$ and PM_{10} (HEI, 2013), and that once UFPs are in the bloodstream they can diffuse into all organs (Ohlwein et al., 2019), including the brain where they are causally linked with neurodegenerative conditions such as Alzheimer's disease (Maher et al., 2016). Associations have been found between children's health and exposure to UFPs, especially in children with respiratory diseases (da Costa e Oliveira et al., 2019).

Through pursuing these two threads side by side, I show all of the mediations that took me from (particulate) matter to form. In doing so, I draw upon Latour's (1999) concept of circulating reference to show how the final representation of the air (RMS 2) was generated and stabilized. RMS 2 speaks with great authority about when and where the air is better or worse, and why this might be the case. However, Latour (1999: 78) argues that we should not take "science for realist painting, imagining that it made an exact copy of the world." In other words, we do not travel directly from matter to form, or from the air to the written text and visual figures of scientific articles. Instead, Latour argues that scientific knowledge is created – and maintained – through a gradual process of moving from matter to form.

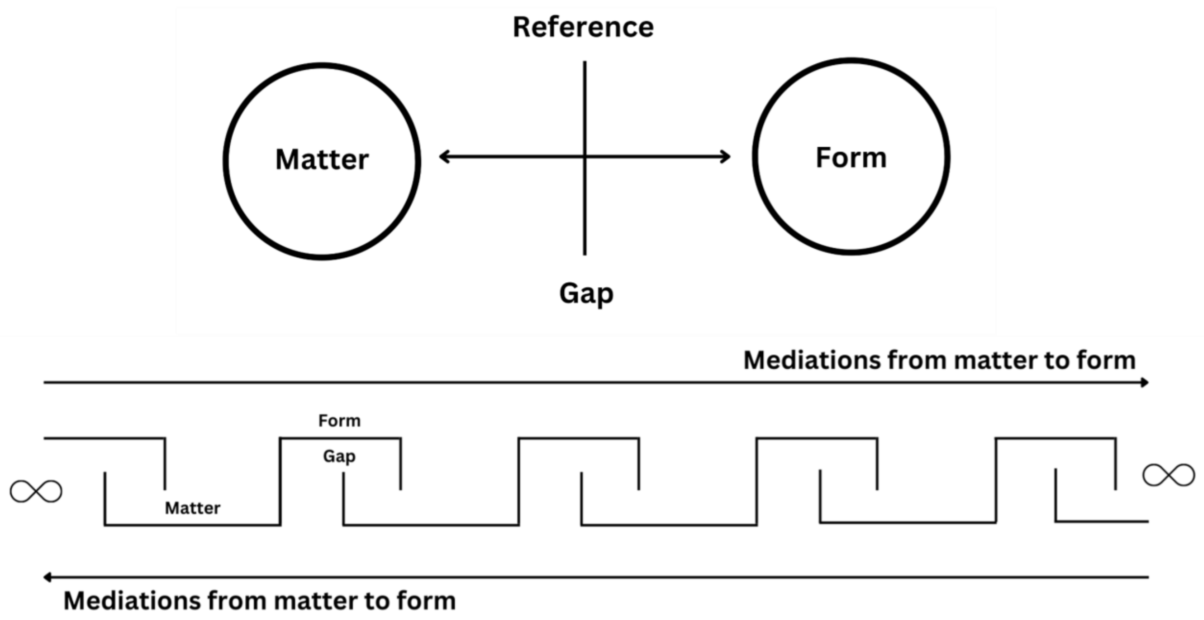

Figure 4.2: Different ways of conceptualising going from Matter to Form. Adapted from Latour (1999). The top part of the figure shows a traditional view whereby the gap between matter and form is bridged using a single reference. The bottom part of the figure shows the circulating reference, whereby the gap between matter and form is bridged in a series of smaller steps.

This difference in thinking is shown in Figure 4.2, where the movement between matter and form as one great leap across a knowledge gap is contrasted with the movement being chain-like. This chain is formed from ‘links’ of scientific knowledge production, where the scientist takes the most essential aspects from the previous link to create a new form of representation, and subsequently a more abstract and less contextualized representation of the world. This representation becomes the reference in the next stage, and this process continues until the final representation is reached. Not one of these references makes the air known, but when placed alongside each other, one can move back and forth along the chain of mediations and translations to see how the written text and visual figures of scientific articles relates to the world. Latour (1999) refers to this process as circulating reference, a concept he illustrates through an ethnography of researchers in Boa Vista in the Brazilian Amazon, investigating whether the savanna is encroaching upon the forest, or vice versa. Latour (1999: 79) illustrates how the researchers, “through a series of uniformly discontinuous transformations”, transform the forest into soil samples, colour charts, and finally into a report that answers their research question. At each stage, they are not directly speaking with the Brazilian Amazon, but through a series of transformations involving a network of human and non-human actants, an understanding and meaning of the forest and its dynamics is constructed.

Likewise, there are many transformations that occur to go from *particulate* matter to form. Or as Weber (2021: 181) puts it, “a lot of work needs to be done to hold these complex assemblages of people, places, materials and technologies in place to produce scientific data.” This is what I do in this paper. It is through using the concept of circulating reference that by looking at an air quality time series (see Figure RMS 2.1) we can link ourselves to the air indoors and outdoors at this school. As such, I trace the steps taken to get from matter to form, steps that are often obscured in the standard reporting of air quality science. I begin by foregrounding my identities and role as the network translator.

RMS 2: Results

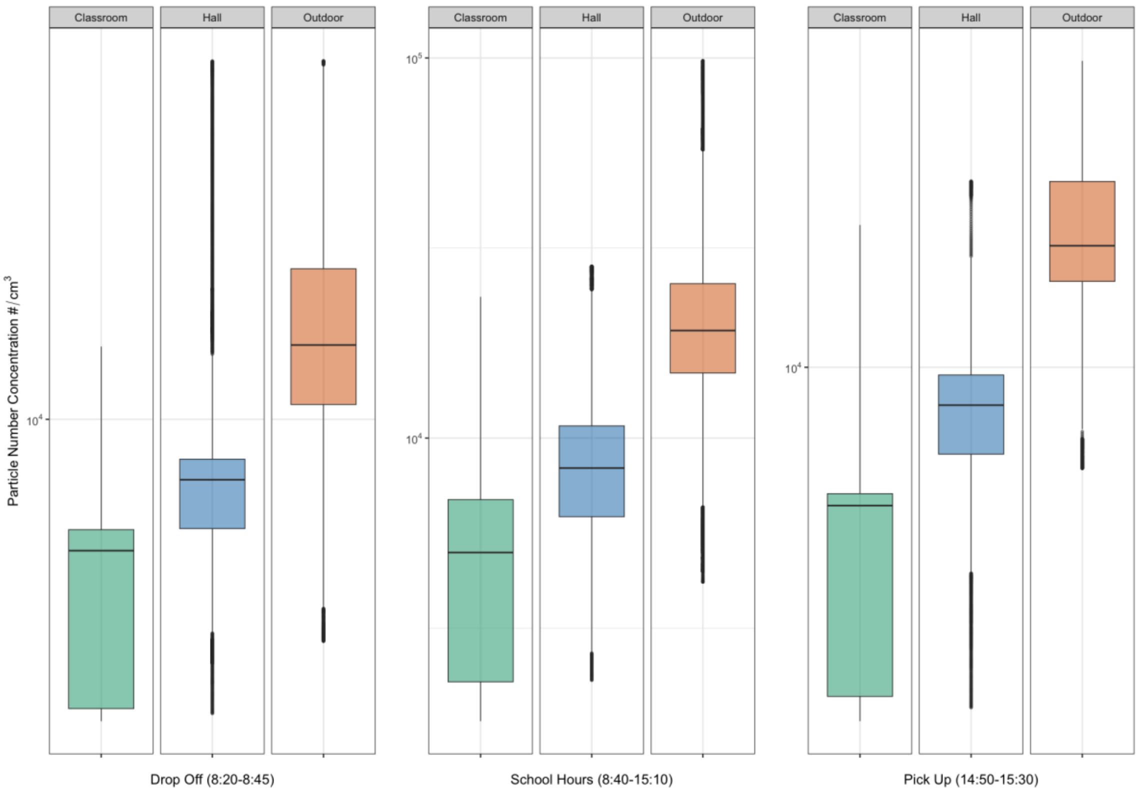

Figure RMS 2.1: Box plot of the daily mean PNC across the three measurement locations, and at three different time periods. The lower and upper box boundaries represent the 25th and 75th percentiles respectively. The line inside the box is the median value.

Figure RMS 2.2 compares the particle number concentration (PNC) across the three locations and periods of the day. The mean PNC for outdoors was highest during all periods of the day (see Table RMS 2.1). On the other hand, the PNC in the classroom was lowest across all the observed time periods. This finding agrees with other studies which observed a strong spatial gradient associated with UFPs decreasing with distance from the road (e.g. Hitchins et al., 2000; Zhu et al., 2002; Hagler et al., 2009). This spatial pattern is the same for the maximum PNC in the three locations.

Table RMS 2.1: Descriptive statistics of Indoor and Outdoor PNC concentrations during different time periods.

	Classroom					Hall					Outdoor				
	Mean	**Min**	**Median**	**Max**	**SD**	**Mean**	**Min**	**Median**	**Max**	**SD**	**Mean**	**Min**	**Median**	**Max**	**SD**
Drop Off	4646	2127	5102	17,205	2786	7580	2277	7377	36,063	3902	20,771	3106	15067	63,568	16,052
School Hours	4825	1800	5000	23,524	2854	9294	2305	8341	28,293	4214	21,546	4183	19,180	98,256	11,193
Pick Up	4785	1976	5307	19,197	3404	8523	2103	8408	23,454	2376	18717	6293	17453	40,713	6624

A similar pattern is seen in the differences in the standard deviation (SD) between the different locations, with a larger spread in the data for the outdoors decreasing with distance from the road (apart from in the hall during pick up hours). This pattern can also be seen in Figure RMS 2.2 which shows daily cycles of 10 minute averaged indoor and outdoor PNC: the diurnal variation was smoother for the PNC indoors rather than outdoors, indicating no significant indoor source of UFPs (Koponen et al., 2001). In most cases, the mean and median are within 10%, consistent with a normally distributed data set (despite outdoor during the drop off time period), justifying the use of the statistical methods used to interrogate the data.

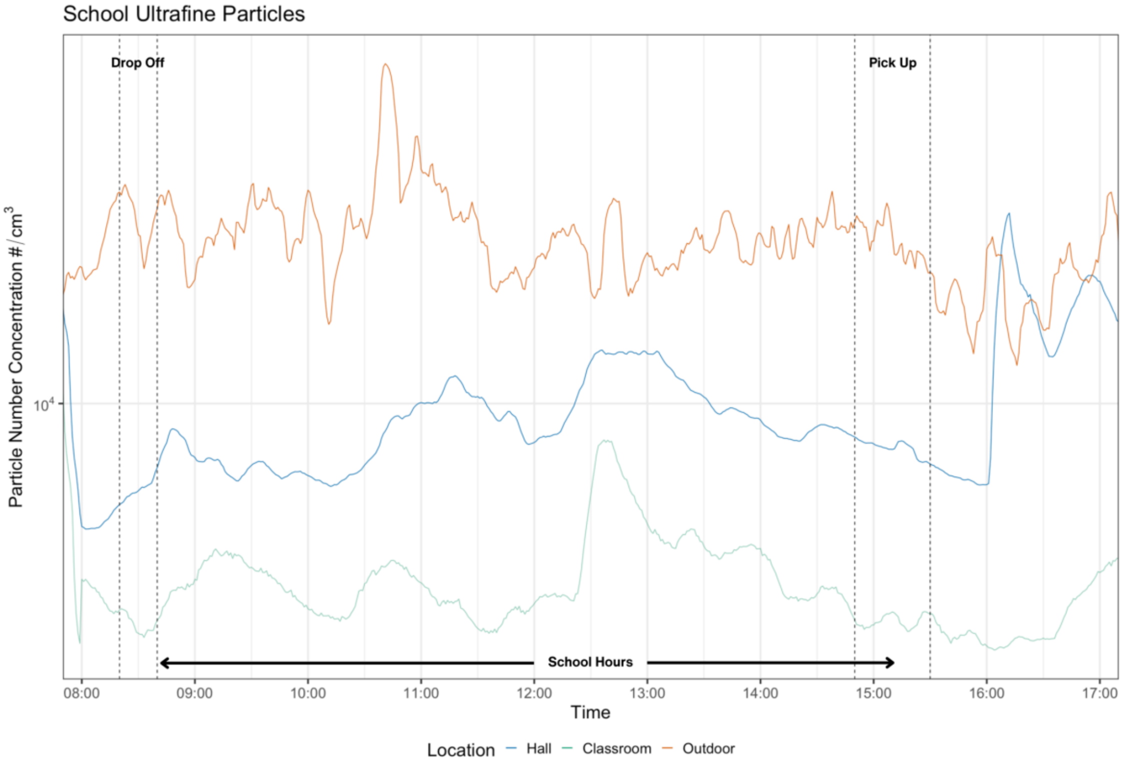

Figure RMS 2.2: Averaged daily cycle from all of the indoor and outdoor PNC measurements.

As with the similar study of Mazaheri et al. (2016), we observed a small increase in PNC at both indoor locations before the start of teaching hours (see Figure RMS 2.2), either associated with early morning cleaning (Morawska et al., 2009), or cooking related emissions from a pre-school breakfast club. PNC indoors continued to rise to another midday peak, likely due to new particle formation events from photochemistry induced nucleation processes (Morawska et al., 2008; Salimi et al., 2013). PNC continue to decrease indoors until between 16:00 and 17:00. In the hall from 16:00 onwards, PNC are at a relative parity with the outdoors, likely due to increased air change rates through the opening of windows directly onto the main road outdoors. PNC in the classroom begin to rise around 30 minutes later indicative of a time-lag. Additionally, as shown in Table RMS 2.2, the ratio of the indoor to outdoor PNC is <1 across all different time periods, consistent with no significant indoor sources of UFPs and with traffic ingress being the dominant source.

Table RMS 2.2: Indoor / Outdoor (I/O) ratios for PNC averaged over different time periods (calculated from instantaneous values).

	Outdoor	**Hall**	**Classroom**
Drop Off	1.0	0.36	0.22
School Hours	1.0	0.43	0.22
Pick Up	1.0	0.46	0.26

4.2. The bicameral mind: the fractured identities of the research translator

In this section, I focus on my role as the lead research translator. In this project it would not be especially controversial to suggest that I was a mediator: an actant that would "transform, translate, distort, and modify the meaning or the elements they are supposed to carry" (Latour, 2005: 39). Ruming (2009) argues that all research is ultimately a process of translation led by the researcher, who defines the objectives and framing of the research, the methods employed, and how the research is represented.

To investigate my role as a mediator, I employ ANT to look at the relations that were formed as I undertook this research. In other words, what identities I performed. Here, I do not take identity as something that is lurking within, but, as advised by Mol (2002), as something that is performed through practice. ANT can allow for pertinent reflections on the roles of human actors in the doing of research, in particular through autoethnographic reflexivity (Sheehan, 2011). If the researcher is the builder of an actor-network, we must recognise their positionality to understand the influence of actants beyond the immediate research programme (Ruming, 2009). This can help us to understand how many people are at work within the researcher, and which version(s) is/are most dominant. This is an important point, as "no one knows how many people are simultaneously at work in any given individual" (Latour, 2005: 54). In other words, this is to accept that the research translator does not have a fixed identity and is equally an actor-network that is in the process of becoming stabilised. These identities can change as new actors are enrolled, and as one decides which actors to represent and which to not (Ruming, 2009).

This is one of the only sections of the paper that does not have an RMS thread associated with it. This is an omission by design, since researcher identity would not be mentioned at all in a traditional environmental science account, as it would be argued to have no effect (in principle) on the science that was done. An air quality science account, dominated by logical positivism, would see 'following the science' (see RMS 1) as enough to explain why I acted the way I did. There may appear to be some elements of human exceptionalism here. However, recognising that the researcher determines the final research translation still raises the question of what non-humans had influence on them: this positionality can then be mobilised to investigate a diverse set of actants (Ruming, 2009).

In this section I outline two main identities that had significant influences on my activities during this project:

1. PhD Researcher at Lancaster University: Lancaster University consists of a wide array of human actants, including my supervisors, members of ethics review panels, fellow PhD Researchers, administrative staff, and many others. My Lancaster University identity also includes a pre-existing structure in place that was sympathetic to my research interest in environmental justice (EJ): it is impossible to ignore the potential effect of my lead supervisor, who is the lead person in my department writing on EJ.[23] Lancaster University also consists of an abundance of non-humans, including digital infrastructures, journal papers, institutional departments, and expectations of what is required to get a PhD.

2. Co-Founder & CEO of National Air Quality Testing Services Ltd (NAQTS): NAQTS is the business that I co-founded and run, the funder of this PhD, and the designer and owner of the air quality monitoring devices which I used in this project and my wider PhD research. Bringing NAQTS to the fore involves examining the motivations of the company (which I help to direct, and am spokesperson for), especially in a context of increased collaboration between universities and industry. For NAQTS, this project helped it to explore the methodology required to provide a schools IAQ testing service, including how to measure, analyse, and report the data; identifying the challenges of installing IAQ monitors in schools; and what it can do to improve its IAQ monitoring technology for future applications. On top of this, supporting this research would also act as a mechanism to show that it is actively engaged in school air quality research, making it well placed as an air quality monitoring partner for future projects.

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[23] The same could probably be said about me using ANT in my this paper, given Lancaster University's strong history of using and developing ANT! (i.e. Centre for Science Studies, 2000).

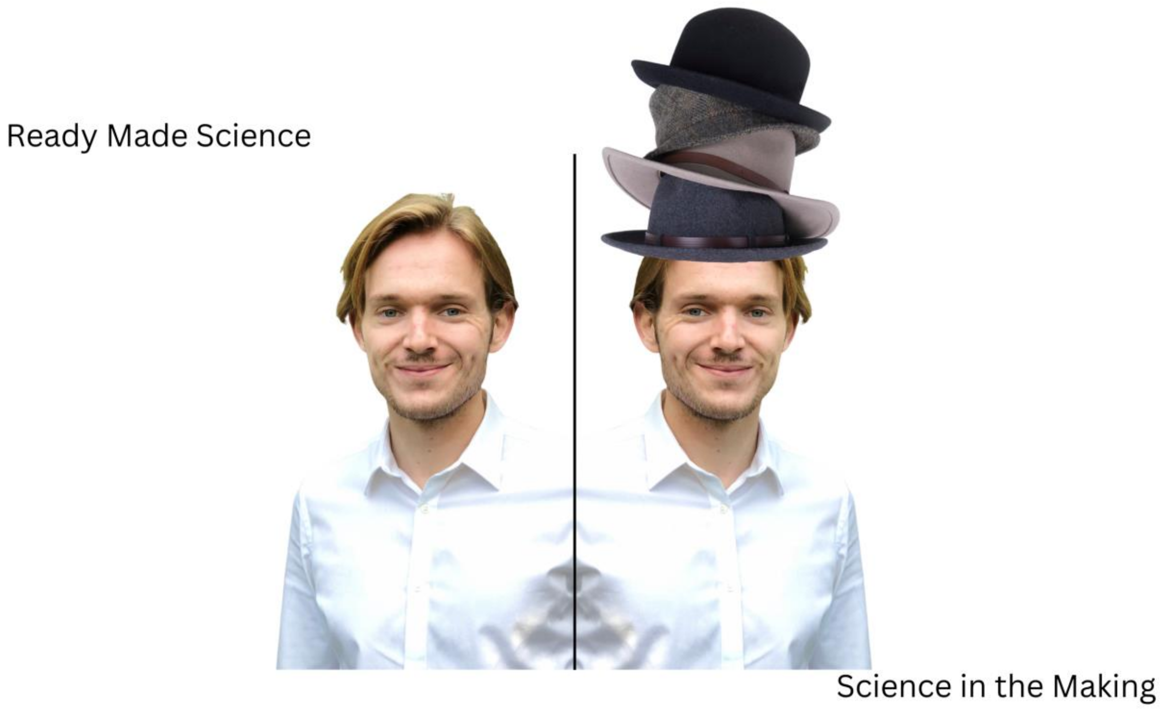

Figure 4.3: My multiple identities that become visible through looking at Science in the Making.

Just as Figure 4.1 showed my two faces, here in Figure 4.3 the multiple hats that I am wearing are brought to light. Figure 4.3 shows more than two hats that I mobilise in this paper, in part as a recognition that there may well be other identities that came to bear upon my actions in this project. While using the hat metaphor, I do not mean to convey that they are identities that I can willingly put on or take off: they are always present (Kohl, 2019). Before detailing how these identities influenced the doing of air quality science in this case, I first outline the second actant, and subject of my study, ultrafine particles.

4.3. Enrolling the invisible: Ultrafine Particles

Ultrafine particles (UFPs) are a component of particulate matter (PM), defined as PM with a diameter smaller than 0.1 microns (μm).[24] UFPs are so small that they cannot be seen under any wavelength of visible light and are dwarfed by other microscopic items, including other components of PM, such as $PM_{2.5}$ (see Figure 4.4). UFPs come from both primary emissions, especially those related to residential wood burning and

[24] This is also referred to as 100 nanometres (nm). Both units will be used when talking about UFPs.

transport, and secondary sources, through chemical reactions in the atmosphere (AQEG, 2018). UFPs are a heavily localised and dynamic air pollutant: whether it is related to a car driving past, or the blowing of the wind, UFPs can change by an order of magnitude within metres under certain circumstances, and several orders of magnitude within seconds (AQEG, 2018).

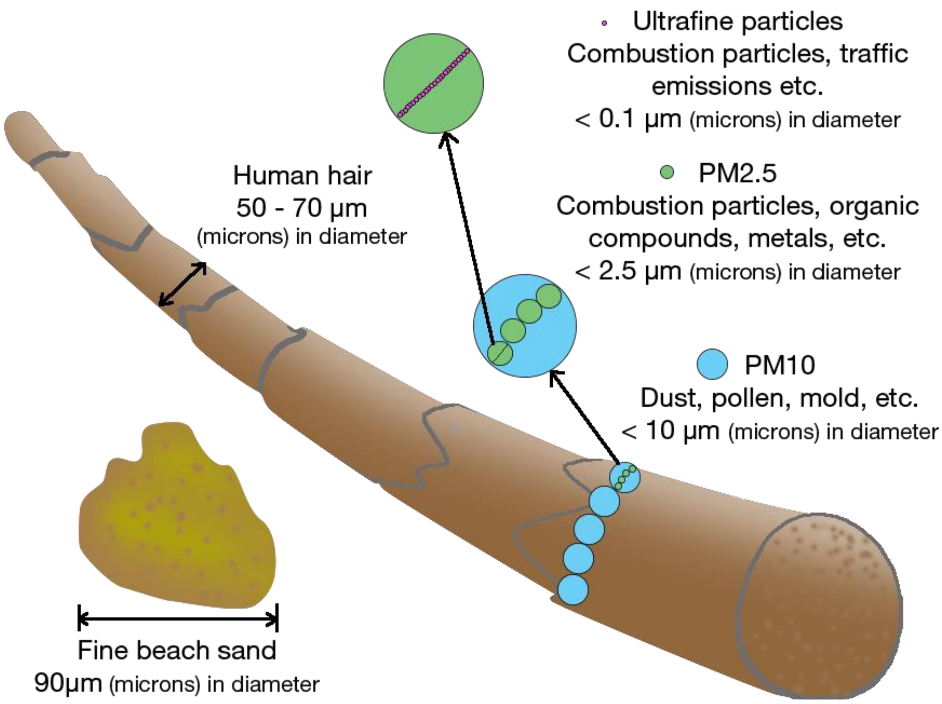

Figure 4.4: The size of different fraction of particulate matter (VFA Solutions, 2017).

RMS 1 outlines the reasons why measuring UFPs is important, including a dearth of measurements and potential for significant health effects (especially for children). However, in doing so, UFPs are designated as a static entity, waiting 'out-there' to be measured by the air quality scientist. Yet, in this paper, I do not simply aim to take UFPs as a "pre-given entity, which can be measured, ordered and categorised, but as an actor in a network which enrols, interacts with and relates to other actors in the network", allowing its "semiotic, material and agentic properties [to] become more visible" (Cupples, 2009: 212).

The presence or absence of UFPs is associated with a range of activities and processes, including, importantly, the "use of mobility technologies (cars, vans, lorries, motorbikes) as people and goods are moved through the day" culminating in socio-temporal structures such as the rush hour, which generates "repeating accumulative peaks in traffic and pollution levels focused along particular routes and into particular places" (Walker, Booker, & Young, 2022: 577). These associations are illustrated in Figure 4.5 which shows the socio-temporal dynamism of UFPs across the city of Lancaster as measured in a separate project (Amos et al., 2022).

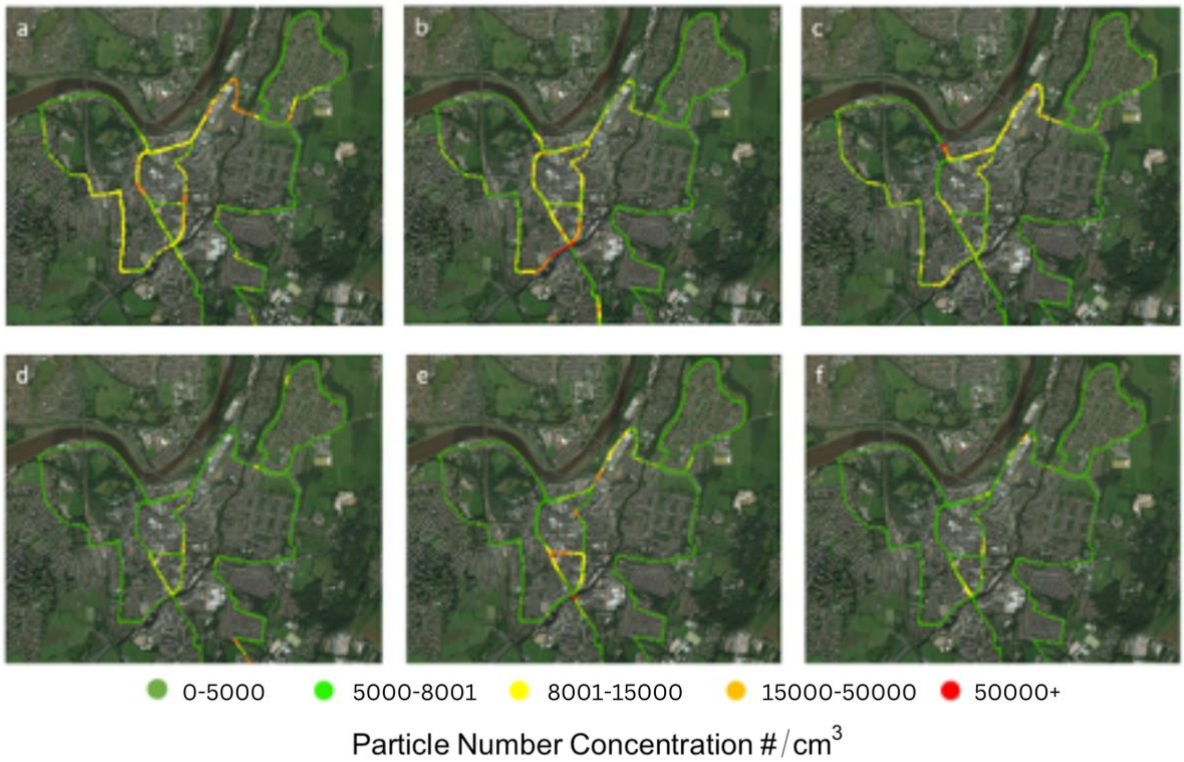

Figure 4.5: Ultrafine particle concentrations (expressed as Particle Number Concentration [PNC]) across Lancaster (Booker, 2019). Red designates higher PNC, and green designating lower PNC, showing 'hotspots' that themselves change across space and time.

Moreover, the formulation and circulation of UFPs are strongly linked to atmospheric processes and conditions, including photochemistry, temperature, humidity, wind speed, and solar radiation (AQEG, 2018). It is in this sense that "the atmospheric environment emerges as both an actor as well as a network" (Cupples, 2009: 213). UFPs are ubiquitous and elusive: while there are typically thousands in every cubic centimetre of air, a single UFP can arrive and disappear within seconds, whether it is blown away by the wind or collides with another UFP or other atmospheric constituent. And just as one UFP departs, another arrives as a car drives past. Yet, UFPs are elusive as they are difficult to measure, in part because they are so small. For my air quality monitoring project, UFPs first must be willing to be enrolled, which involves a period of negotiation between me and my IAQ monitor, the NAQTS V2000.

4.4. Opening the blackbox: The NAQTS V2000

Bijker et al. (2012) have argued that we should not separate the study of science and technology. Highlighting the important role of scientific instruments in technoscientific practices has been a cornerstone of science and technology studies (STS). From Latour and Woolgar's (1979) mass spectrometers, to De Laet & Mol's (2000) water pump, to many others (see Baird, 2004), technologies have been at the forefront of the development and circulation of new scientific knowledge. The same follows for air quality science where air quality monitors shape our relations with the air. For example, Whitehead (2009: 15) has detailed the role that different air quality monitoring instruments have played in practices of air governance in the UK, including the "construction of a scientific apparatus of and for government." Relatedly, Ottinger (2010) has outlined how citizen science activist groups affected by air pollution have strategically enrolled different air quality monitoring technologies to contest industry and governmental representations of the air.

Of course, to claim that air quality monitoring technologies play an active role in the construction of scientific facts is not to say that air quality monitors alone determine the actions of scientists. Rather it is to say that air quality monitoring technologies can make a difference to how – and which – scientific facts are constructed (Latour, 2005). If one treats the air quality monitor as an intermediary, something that "transports meaning or force without transformation" (Latour, 2005: 39), then knowing the scientific reasons behind its original development is enough to know its role in science in the making. However, if we treat the air quality monitor as a mediator, it might emerge as something that makes a difference to the scientific facts that are constructed. Highlighting this agency can help us to "better understand why certain forms of air quality knowledge were constructed" (Whitehead, 2009: 125). It is in this vein that I interrogate the NAQTS V2000 (hereafter V2000; see Figure 4.6), an IAQ monitor that I co-created, which is the core product of the company that I run and measures several different air pollutants.

Figure 4.6: The V2000 with and without its outer casing from the front and the back.

The V2000 is both an actor-network, consisting of various air quality sensors, electronics, and algorithms, and an actant, which enrols – and is enrolled into – other actor-networks in the process of doing air quality science. Before delving into the specific role that the V2000 played during its enrolment into my study, this is a good opportunity to begin to prize it open, both as a literal and figurative 'black box'.

4.5. Developing the V2000

Suchman (2002: 95) aptly states that "professionalized producers of technologies are themselves enmeshed in webs of human actors and nonhuman actants only partially visible to them, which form a kind of naturalized landscape in relation to which they do their work." Callon (2012) argues that the early stages of technological development often omit this naturalised landscape of economic, social, and political influences, instead framing technological development as solely technical. In this section, I wish to explore this naturalised landscape to show how the V2000 was not designed from nowhere, and to see the relations that were embedded within it from its inception. There is also no RMS thread in this section as, in the concept of RMS, the V2000 is already stabilised as an intermediary and subsequently black boxed.

As is often the cliché of business and technology development, the V2000 was initially developed in the basement of my family home (see Figure 4.7).[25]

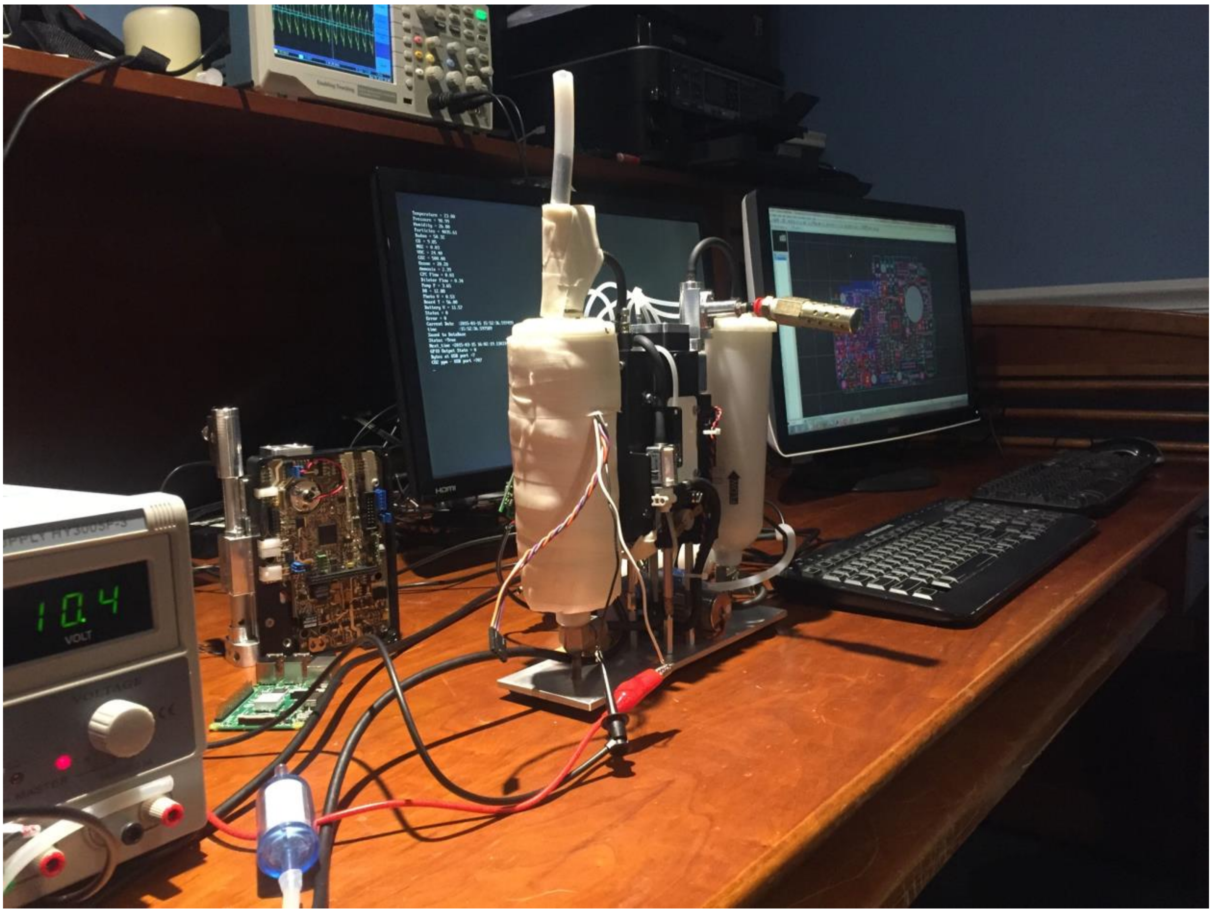

Figure 4.7: A prototype V2000 being tested in the basement 'laboratory'.

The V2000's development was spearheaded by the founders of NAQTS: me, my father (Dr David Booker), and my uncle (Simon Booker). David and Simon have worked closely for many years developing new technologies centred around characterising the emissions generated by internal combustion engines, and this was my first collaboration with them. David and Simon had experience developing the core sensor in the V2000 (something I return to shortly), as this sensor is an integral part of a portable emissions measurement system (PEMS). These are devices used in the on-road testing of vehicle emissions, which have become well known following the 'Dieselgate' scandal that saw the Volkswagen Group cheat official emission tests by minimising vehicle emissions during official testing while flouting the limits during 'real-world' use (Brand, 2016). As someone who was not a trained aerosol scientist or

[25] In fact, the V2000 began as the V1000. It was not until after some upgrading and rebranding it became the V2000. However, for simplicities sake I use the name V2000 throughout.

engineer (something that I have somewhat reluctantly become over the past 8 years!), my position was concerned with the mission of the technology: what it was going to be used for, how we could develop it to meet customer requirements, and ultimately how this would become a profitable business opportunity for NAQTS. I saw an opportunity arising from the strong interest in outdoor air quality not being matched for IAQ, despite its importance (outlined in RMS 1) and wanted to develop a service to provide IAQ information. However, at that moment in time there were no suitable IAQ monitoring devices on the market: so we decided to make our own.

While the V2000 measures many different air pollutants, for this paper, I focus on the sensor that generated the UFPs data. This sensor is called a condensation particle counter (CPC), which is a device used to count the number of particles in the air through an assemblage of technical elements, including voltages, pumps, and working fluids (see Figure 4.8). Different types of CPCs have different operating mechanics (see Lowther et al., 2019).

The NAQTS V2000 operates as follows (see Figure 4.8):

1. HEPA[26] filtered air enters the saturator block where it mixes with a controlled flow of the working fluid (Isopropyl Alcohol – IPA). This flow is managed through the liquid level sensor, which detects when the saturator block needs more IPA. When it does, it triggers the peristaltic pump to fill the saturator from the IPA tank. The resulting mixture is heated to a temperature that is slightly above the saturation point of the IPA vapor, creating a supersaturated vapor of IPA.
2. The supersaturated IPA vapor enters the condenser alongside particle laden air that enters through the sample inlet. The particle laden air acts as a nucleation site for the supersaturated IPA vapour, causing the particles to grow through condensation. These particles are now large enough to be seen by optical laser light scattering.
3. The grown particles are passed via the nozzle through a laser beam. As the particles pass through the beam, they scatter the light, which is then measured

[26] High efficiency particulate air (HEPA) filters are high grade PM filters that remove at least 99.95% of PM at 300nm (the size at which they are least efficient).

by a photodiode that converts the signal into an electrical pulse. Each electrical pulse represents a single particle that has been counted.

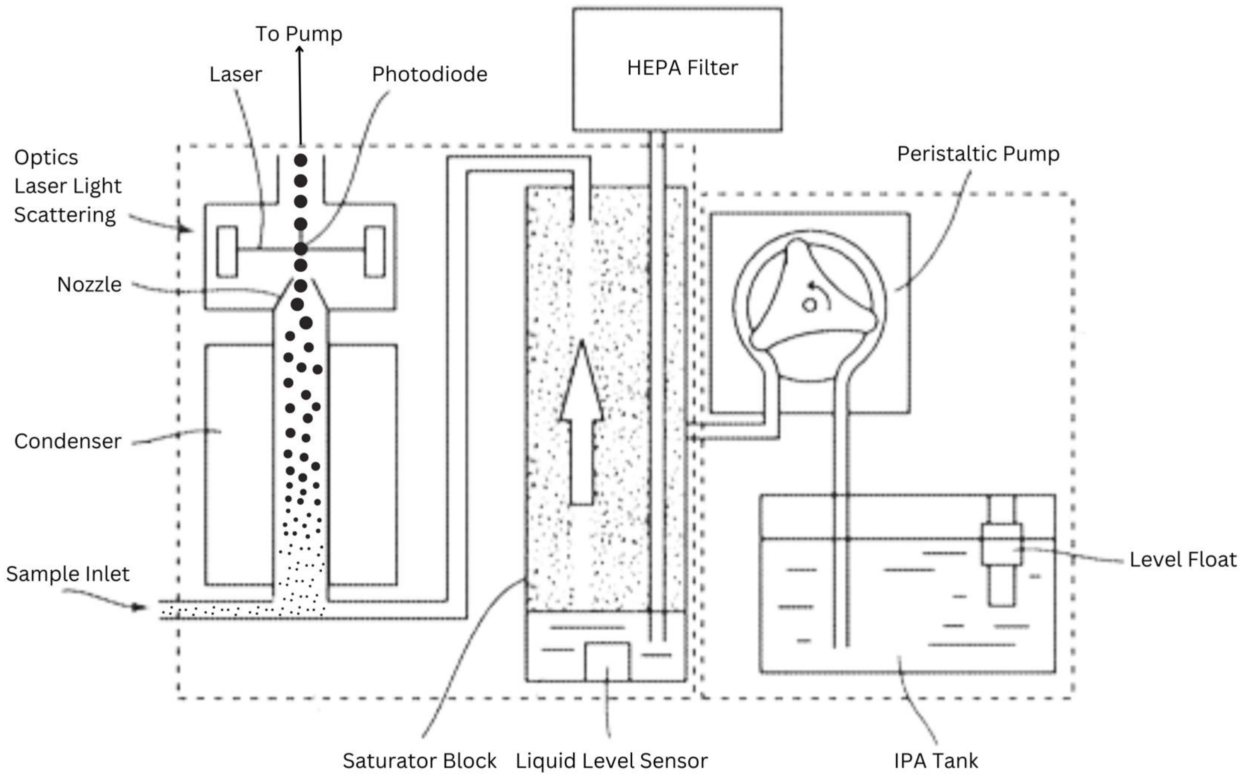

Figure 4.8: NAQTS CPC operating procedure. Adapted from WO2019234688A2 (2019).

At this stage, we have already reduced the air in a number of steps to PM, then to UFPs. In arriving with a measure for UFPs, we need to further transform our reference and represent UFPs as a particle number concentration (PNC). Even then, it is important to note that the CPC does not directly report on the PNC. Instead, a series of additional transformations take us from the particles that enter the CPC into a recorded PNC stored on the V2000. I illustrate this transformation in Figure 4.9 using an oscilloscope, which is a device used to graphically display varying electrical voltages. As a particle goes past the laser in the CPC it scatters light which is converted into an electrical pulse that can be quickly and easily read and stored by the V2000s on board computer. It is this conversion of scattered light into an electrical pulse where particles literally and figuratively come to count.

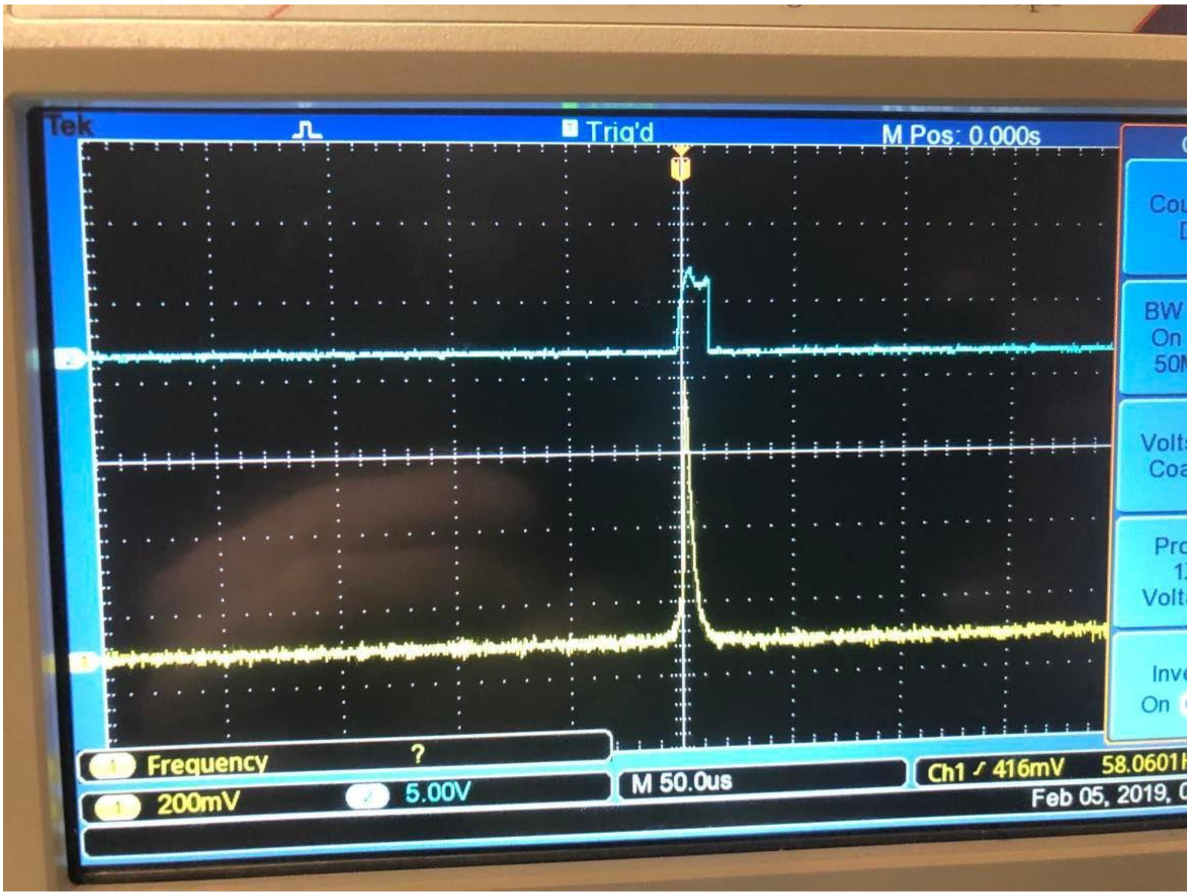

Figure 4.9: An Oscilloscope display showing the process of counting particles through converting scattered light (yellow line) into an electrical pulse (blue line).

It is here that the V2000 becomes an actant as well as a network, as what comes to count as a particle is a judgment of different actants from within the V2000. This somewhat confounds the dichotomy that is often presented between modelling and monitoring air pollution: even devices that appear to measure the air directly rely on their own internal models to transform their workings into representations of the air. As is true of all science, there is always a model.

Devices using condensation to grow microscopic particles, so that they can be detected optically, have been around since the 19th century. From the manual counting of droplets to provide an visual determination of the PNC to devices that measure continuously (McMurry, 2000), over time, aerosol scientists have been able to more reliably measure particles that are smaller and smaller (Wlasits et al., 2020). Treating the V2000 as a mediator, I now further prize open the CPC within it, to see how its internal workings bound ourselves to a certain understanding of the air. I do so through interrogating two aspects of the CPC. Firstly, through understanding the role of the working fluid, and secondly, through its focus on measuring PM by number, rather than mass.

4.5.1. The work of the working fluid

Despite David and Simon's experience in developing CPCs for PEMS devices, the re-engineering of the CPC for NAQTS required the forging of new assemblages within the V2000 to make it more suitable for IAQ monitoring. One of these new assemblages was the working fluid, which is important since it condenses onto and grows the particles, allowing the particles to be made visible and, literally, come to count. The working fluid works closely with other parts of the V2000. However, it can disrupt network stability by contaminating other sensors in the V2000, and/or saturating the optics with homogenous nucleation (vapour condensation forming its own droplets), meaning the device counts particles it generates itself. As such, all CPC technologies and working fluid selections are trying to minimise homogenous nucleation and instead promote heterogenous nucleation (particles acting as the nuclei for vapour condensation to form droplets). A classic example illustrating heterogeneous nucleation is in cloud formation, where water molecules condense onto the surface of particles (Winkler and Wagner, 2022).

There are three commonly used working fluids in CPCs: butanol, IPA, and water. Butanol has a number of benefits and has been used in most of the historical research on UFPs (TSI, 2015). Notwithstanding these advantages, butanol was not suitable for our application because of its pungent odour (making enrolment into indoor environments difficult), associated negative health effects (e.g. Segal et al., 2020), and relative difficulty to procure. This left us with water or IPA. We decided upon IPA, because it is less smelly than butanol, provides excellent condensational growth (especially for carbonaceous particles), is a relatively benign chemical, and is easy to procure. Water would perhaps have been better with regard to odour. Alas, we did not have the expertise at the time to develop a water CPC which has a different operating mechanism. Moreover, water as a condensing agent tends to work less well for particles of an organic composition (Kangasluoma et al., 2014), a core component of particles emitted from vehicles (Gentner et al., 2017).

What would perhaps be relegated to a technical discussion in a journal on aerosol science technology (rather than air quality science) is instead enlightening of what air quality worlds this instrument makes more visible. While we are literally counting the number of particles in the air, the working fluid influences the likelihood of enrolment of some particles over others. Just as for Callon's (1984) scallops, which were only enrolled after they first anchored themselves to collectors that would allow them to grow, our particles first had to be willing to anchor themselves to our working fluid.

4.5.2. What particulate matter comes to count? Measuring particles by number and mass

There is no one, universal particulate matter (PM). Instead, there are a variety of metrics that translate measured concentrations of particles into PM (Lowther et al., 2019). Reminiscent of the concept of "boundary objects" (Star, 1989), PM is stable enough that different groups can work together on it, but also disparate enough that there is often disagreement on what it is that they are actually working on. While the working fluid literally affects which particles are seen by the V2000 – and in doing so prioritises some composition of PM over others – the categorisation of PM by number or mass also affects what is observed. The limited way in which this information is normally provided is shown in RMS 3.

RMS 3: Measuring Particulate Matter by Number and Mass

CPCs are used to measure UFPs by measuring PNC. While this approach counts all particles up to 2.5 microns, the size distribution of ambient aerosol is typically so heavily skewed towards particles in the UFPs range, that simply counting particles is an accurate proxy measurement (Morawska et al., 2008): UFPs are typically >90% of the total number of particles in the air (AQEG, 2018).

Measuring PM by number (PNC) involves the literal counting of particles in a fixed volume of air. Conversely, measuring by mass involves the weighing of PM on a filter. In fact, the V2000 does actually measure $PM_{2.5}$ as part of PNC, but, as you can see in Figure 4.10, the number of particles at that size compared to those in the UFPs size range means that they come to count for nothing: they are the equivalent of a needle in a haystack. Likewise, the definition of $PM_{2.5}$ includes PM in the UFPs size range. However, when measuring by mass, UFPs have negligible mass compared to larger sizes of PM under 2.5 microns.

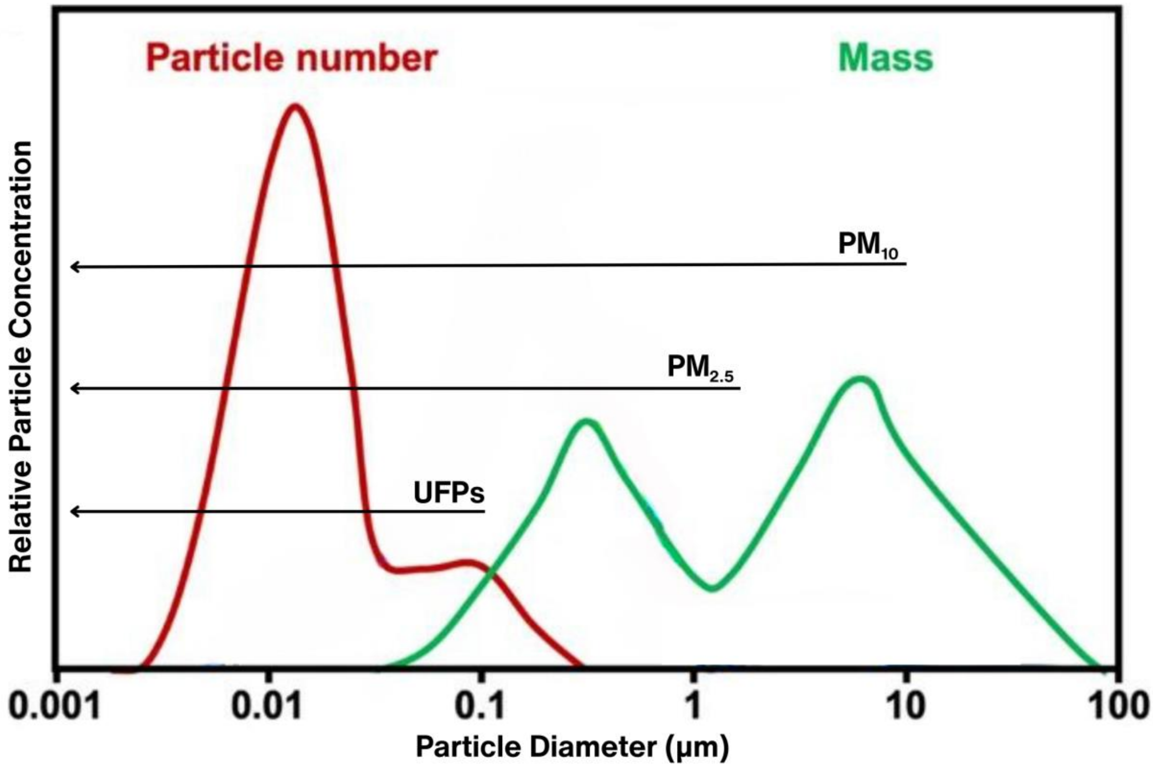

Figure 4.10: Illustrative particulate matter number and mass distributions. Figure adapted from Kwon et al. (2020).

This multiplicity in PM is typically acknowledged in the introduction of a journal article, outlining the importance of measuring different metrics of PM (RMS 4). However, embedded in this categorisation is a whole set of relations. Through measuring the air by number, one emphasises local pollution sources and, therefore, different responsibilities for their emissions (or clean up). Put differently, *how* you measure the air affects what is seen and what should be done to improve air quality. As shown in RMS 4, these factors are given a cursory glance. However, in doing so they take PM solely as a static object out there to be measured and ordered by air quality scientists.

These tensions illustrate how different understandings or relations to the air can cause harm. This has been highlighted in EJ disputes around other air pollutants, particularly for citizen science projects measuring different pollutants in different ways (e.g. Ottinger, 2010; Gabrys, Pritchard, and Barratt, 2016).

RMS 4: The importance of measuring particle number

PM tends to be measured by mass, especially through the regulated standards of $PM_{2.5}$ and PM_{10}, which are backed up by metrological chains dictating what instruments to use, how and where to measure, and over what period of time, established in part based on epidemiological and toxicological research (WHO, 2021). Whereas, notwithstanding PNC being measured at the tailpipe, there are no UFPs air quality standards worldwide (AQEG, 2018). Of particular importance is that PNC and $PM_{2.5}$ have different sources and drivers, and therefore do not always correlate (De Jesus et al., 2019). PNC is highly susceptible to local sources, in particular vehicle emissions, with meteorological factors also being important for dispersion and secondary particle formation, whereas $PM_{2.5}$ can stay airborne for weeks and be transported long distances: some estimates attribute 21-30% of $PM_{2.5}$ to originate from non-UK sources (AQEG, 2013). Moreover, of the UK based emissions that people in urban areas are exposed to, rural 'background' concentrations contribute significantly. For example, in major urban areas of southern England, 60–80% of background $PM_{2.5}$ concentrations come from rural sources (AQEG, 2012). A recent study suggests that agricultural emissions of ammonia contribute substantially to $PM_{2.5}$ concentrations in cities around the UK (Kelly et al., 2023). This highlights that control measures aiming to reduce $PM_{2.5}$ do not automatically reduce PNC, and vice versa (De Jesus et al., 2019).

The creation of the CPC and selection of working fluid was not the end of its development. Before it was to be accepted as a valid instrument to measure UFPs, the strength of its measurement capabilities would have to be tested and characterised.

4.5.3. Metrology: measuring the right relations

Metrology, the science of measurement, is what Latour (1987: 251) refers to as "the name of this gigantic enterprise to make of the outside a world inside which facts and machines can survive." It is an important part of air quality science and before the V2000 would emerge as an agential actant, the quality of its sensors first had to be tested to characterise the value of its data. These "metrological regimes" (Barry, 2002) have been designed to create a universal way of knowing, sensing, and reporting on the air. They are comprised of an array of actants, including registered laboratories, international organisations, standard operating procedures, calibration pollutants, and reference air quality monitors. This is of particular interest when using an ANT lens because it shows how local practices are made to be global. In this case, it is how measuring – and knowing – the air in Lancaster in 2019 can be compared with another location at another point in time, whether that be with, for example, Los Angeles in 2019 or Lancaster in 2023. For Latour (1987), metrology allows actants to become "immutable mobiles": objects that are stabilised by actor-networks, allowing them to reproduce their actions in different places. It is through bringing these immutable mobiles into "centres of calculation" (Latour, 1987) – venues where knowledge production is stabilised – that the construction and dissemination of knowledge can move more easily to other places. In this section, I focus on the metrological practices that were undertaken with the V2000s before they were deployed.

There is a long history of paying attention to testing procedures when studying technology (e.g. Constant, 1983). Doing so can help to widen the net of actants involved in producing our understanding of the air, connecting it to things such as "practices of environmental concern, sensor manufacture, electrical engineering, [and] algorithmic processing" (Pritchard et al., 2018: 4535), as well as embodied researcher 'feeling' for their instruments (Garnett, 2016). I focus on two specific metrological practices: calibrating the V2000 against an external standard and collocating – or 'normalising' – two V2000 units with each other.

Calibrating the V2000 against an external standard enrolled the International Organization for Standardization (ISO), a centre of calculation that develops international standards for products, services, processes, materials, and systems (ISO, 2018). More specifically, this involved the metrological standard ISO 27891 (ISO, 2015), a standard to determine the detection efficiency associated with a CPC. ISO 27891 is a socio-technical assemblage consisting of instruments from particle generators, classifiers, and other CPCs (see Figure 4.11). Barry (2002) might argue that ISO 27891 is as much about legitimising the roles of experts and cultivating a culture of regulation, monitoring, and compliance, as it is about ensuring accurate measurements. These instruments are themselves part of other metrological chains and accredited by separate ISO standards (ISO, 2017).

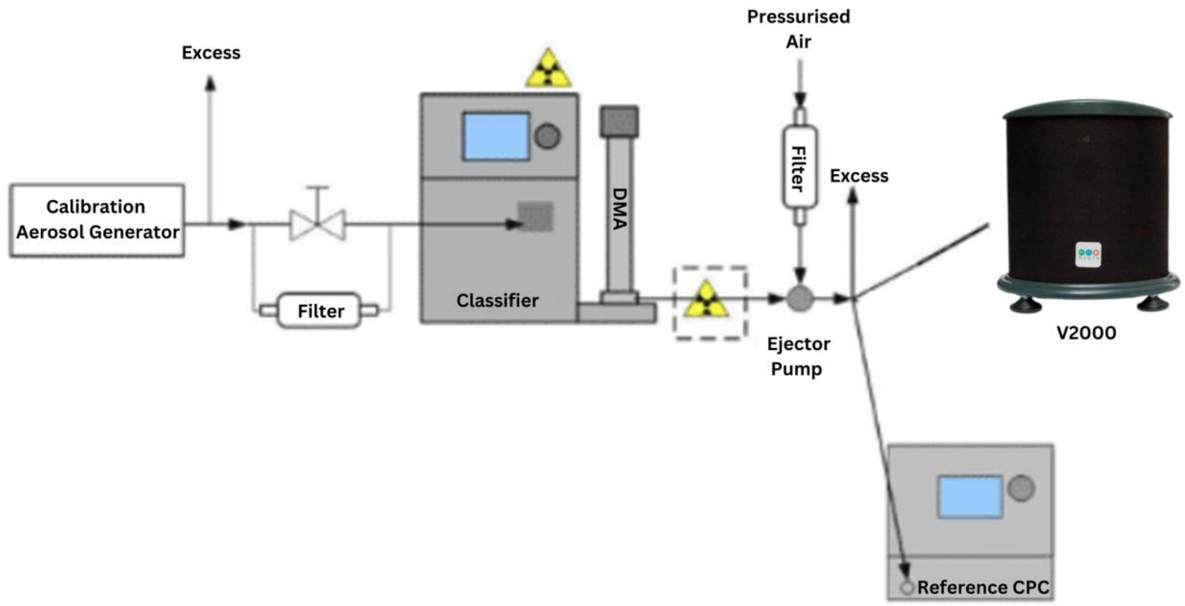

Figure 4.11: ISO 27891 CPC calibration procedure. Adapted from Booker et al. (2017).

As well as being a technical standard, ISO 27891 is also a 5 yearly review process that brings together a technical committee of scientists of both academic and industry backgrounds, who meet to define terms, reference materials, sampling methodologies, and how to interpret results (ISO, 2023). ISO 27891 requires a CPC to be tested against a 'reference' CPC to ensure that it measures similar concentrations of particles at different sizes (see RMS 5). This characterises the 'cut-off', which is the size at which the CPC only sees 50% of the particles present in the air, with lower cut-offs meaning a device will see a greater number of particles (as shown in the particle size distribution graph in Figure 4.10). This cut-off characterisation is shown in the certificate in Figure RMS 5.1. It is this form that becomes the reference for the next stage of the circulating reference: PNC becomes a calibrated V2000.

RMS 5: V2000 condensation particle counter metrology

The detection efficiency of the NAQTS V2000 CPC was characterised by measuring its performance against a reference CPC according to ISO-27891. Both the V2000 CPC and the reference CPC were subjected to a calibration aerosol that was made to be monodisperse and of a particular size. This was achieved by first 'neutralising' the particles in the Classifier with a radioactive source to ensure that they have a uniform charge. The particles were then sorted by their electrical mobility in a differential mobility analyser (DMA). The monodisperse aerosol was then sent to the CPCs. The V2000's CPC counting efficiency was then defined at specified particle sizes over a range of concentrations, with a cut off established at 15 nm.

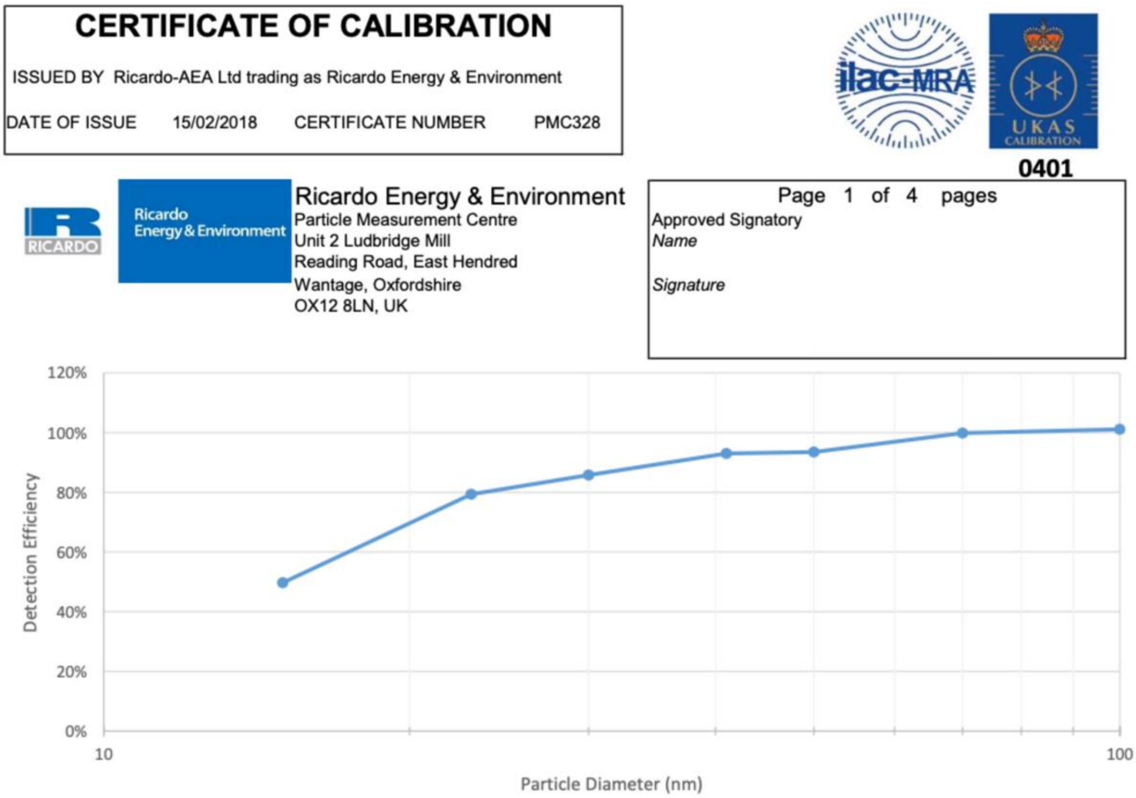

Figure RMS 5.1: CPC counting efficiency certificate.

While the standard air quality account in RMS 5 might be included in an appendix or supplementary information of an air quality science paper, using an ANT lens allows us to investigate the certain set of relations with the air that it embeds. This allows certain actants to speak for themselves, such as the 'calibration aerosol' that was used. As shown in Figure 4.11, calibration aerosols are the particles that are enrolled to make the particles that these CPCs measure commensurable with an established scientific paradigm, and establish the metrological chain. Therefore, their role is to be stable and reproducible so that CPCs can be characterised and calibrated (ISO, 2015). These calibration aerosols are required as one cannot simply take particles from the ambient air to calibrate a device: those would be of different sizes, compositions, and electrical charges, perhaps prone to stick together and react with other things in the air, affecting their size and number.

It is here that the agency of the UFPs becomes especially noticeable. While calibration aerosols can be made from a variety of different materials, during calibration they are enrolled in one material composition: a choice which is made by the calibration laboratory. This manufactured PM-laden air differs from the air outside of the laboratory, which always contains a mixture of different PM materials (Kangasluoma et al., 2014). Here, the multiplicity of UFPs is evident, both as a phenomenon that exists outside in the real-world, but also one that is manufactured to make enrolling the outdoors UFPs easier. As with the working fluid, the calibration aerosol that is used affects what particles are seen. In fact, these two actants work closely together, with working fluids preferring certain compositions of particles (Giechaskiel et al., 2009; Terres et al., 2018) and vice versa (Wlasits et al., 2020). This creates challenges for creating a universal calibration aerosol to represent all particles worldwide. In the end, certain combinations of aerosol material and working fluid come to define what PM is enrolled and therefore comes to counts as PM, and ultimately what counts as air pollution.

This is an area of aerosol science that is far from being stabilised, in part due to the stubbornness of UFPs, which as Latour (2000: 116) remarks about the objects of science (in our case UFPs) "have no scruples whatsoever in […] behaving in the most undisciplined ways, blocking the experiments, disappearing from view, dying, refusing to replicate, or exploding the laboratory to pieces." Indeed, some research has found large differences between the counting efficiency between different particle compositions (Hermann et al., 2007; Wang et al., 2010), and other research suggests much smaller differences (Wlasits et al., 2020). This highlights that UFPs can be particularly challenging to negotiate with, and that different calibration aerosols ultimately represent different natures that are to be enrolled.

After having formally accredited a V2000 CPC with the relevant metrological chain, I then normalised the other V2000's CPCs against it through a period of colocation (see RMS 6). Colocation entails placing an air quality monitor next to a reference instrument[27] and sampling the same air to apply a correlation coefficient to adjust its values so that its data output matches the reference device. This is illustrated in Figure 4.12, where the PNC curves for units 2 and 3 are 'corrected' to make them 'agree' with Unit 1.

[27] This reference instrument is sometimes referred to as a 'golden' unit.

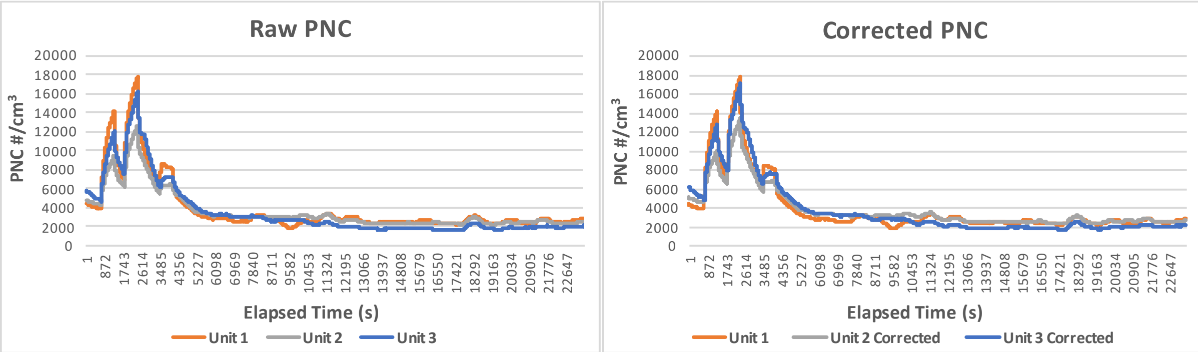

Figure 4.12: Time series displaying the process of normalising CPCs for PNC measurement.

Through calibrating one of the V2000 CPCs to ISO-27891, the other devices become normalised to that one, making them agree on how many particles they are seeing at a given time and in a given space. Even so, as shown in Figure RMS 6.1, the agreement is cordial rather than perfect. That is because my role was to stabilise the V2000 actor-networks as much as possible, obscuring the idiosyncrasies of each V2000 and any subsequent tinkering required to make them agree. Ask any air quality measurement scientist and they will be able to tell a similar story: making one device work is easy, making two work in exactly the same way is another matter.

The normalisation procedures involved engaging with each V2000's mechanical, electrical, and algorithmic components, to ensure that they are stable actor-networks that can be deployed into the real-world of the classroom. This stage is particularly important for the data interpretation to ensure that I am measuring the right relations: that any differences in observed PNC measurements between V2000 devices in the field could be explained by changes in air pollution concentrations, and not the V2000 itself.

RMS 6: Normalising the V2000s

Prior to sampling all V2000 devices were normalised to ensure differences in PNC were a result of changes in air quality rather than differences between the V2000s. Two V2000 devices were collocated against a reference V2000 that had been calibrated according to ISO 27891 (ISO, 2015). Correlation across a range of different PNC showed good agreement (R^2 = 0.96, and 0.94) (see Figure RMS 6.1)

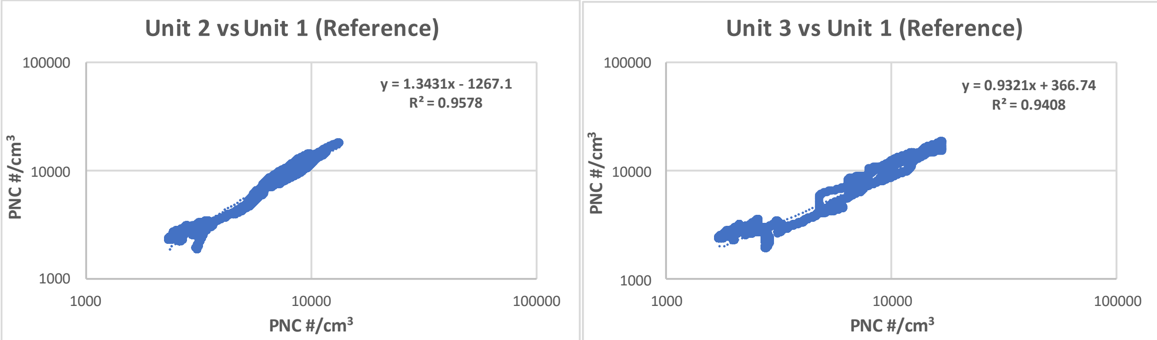

Figure RMS 6.1: Normalisation of two V2000 CPCs against a reference V2000 CPC.

In this measurement campaign, calibration ensured that measurements were related to a recognised standard (ISO 27891) and that the V2000s agreed with each other when subjected to various concentrations of PM, meaning we were measuring the right relations, and that the resulting data would be an immutable mobile. Going through these metrological steps strengthened the claims that could be made around the arising data.

However, I would suggest that it is a partial perspective on the impacts of this metrological regime, and it is not enough to explain why UFPs were chosen. Research on patterns of indoor/outdoor air quality and traffic related emissions could easily have measured the regulated pollutant of nitrogen dioxide (NO_2) which is often used as a proxy for traffic emissions (Salonen et al., 2019). In considering commensurability with a metrological regime, NO_2 is a regulated air pollutant – unlike UFPs – which arguably would make the measurement more relevant. The NAQTS V2000 even includes multiple low-cost sensors that measure NO_2. So why was this not the focus? Firstly, the V2000's NO_2 measurement is less accurate and less well backed up by a strong metrological chain. This is because the V2000 measures NO_2 using a low-cost sensor, which have been available for a much shorter time than regulatory measurement devices, and there is a lack of standard operating procedures for how to use and understand the data from these sensors. This alone could justify a technical reason for why to use the V2000's high-quality measurement of UFPs over the lower-fidelity NO_2 measurement.

However, when reflecting upon the identities that I brought to bear upon my practices, there were other factors that influenced the selection of UFPs. Firstly, enacting my

Lancaster University identity, the shared expectation between myself, my supervisors, and the Lancaster University review system of doing something ‘novel’ to be granted a PhD was a significant factor in the choice to measure UFPs rather than another traffic pollutant such as NO_2. With UFPs’ measurement and analysis being far less ubiquitous than those of NO_2, perhaps due to them being unregulated in air quality, they better satisfy a novel contribution criterion in air quality measurement science. Secondly, it is a much more expensive measurement, so access to monitoring equipment is a significant reason why there are not more measurements. Here I was able to enrol my NAQTS identity so that I would have easy access to the right equipment: I gave with the left hand and took with the right. Thirdly, it would also be remiss not to mention that I acted as a spokesperson for NAQTS to raise the profile of the UFPs (as well as demonstrate that the V2000 could measure them well!). This is an often taken for granted part of the doing of science, which – in a non-mutually exclusive way – does research because it is seen as important (as shown in RMS 1) and also to demonstrate the importance of its subject. This second point is particularly important, as what science is done – and conversely left undone – is at least partially dictated by an ability to secure funding, which brings in a range of other actants and logics for what is done and why.

4.6. The V2000 enters the school assemblage

As the V2000s are taken from the laboratory and put into the real-world, new relations must be formed, raising some areas of potential resistance. In RMS 7, I outline the air quality science justification for the selection of the different monitoring locations within and around the school. However, in the science in the making text, I highlight the role of several network relations that influenced where the V2000s were placed, and ultimately where they made the air visible. Of course, the placement of the V2000s was ultimately a decision that was made by me, the lead research translator, but not without negotiating first with a host of human and non-human actants.

Before delving into the specificities of the V2000s’ locations, it is worth investigating why the air was measured at *this* Lancaster school. My Lancaster University network enrolment certainly influenced this choice. My quest to find an appropriate and available place to measure IAQ began with an email introduction to a local schoolteacher by one of my PhD supervisors. This supervisor had children at the school, had worked with the teacher previously to deliver a Science Week lecture, and their spouse was chair of the school's governors. Of course, concurrent to this practicality, was a scientific justification that would also satisfy the criteria for an interesting case study for my PhD. However, I raise this point, as I believe it important to hammer home that what air quality science is done – or more importantly left undone (Frickel et al., 2010) – is not necessarily based on a purely logical rationale for a perfect location to unearth the air, but instead also influenced by social relations.

RMS 7: Study area and monitoring sites

The air quality measurements were based in Lancaster, a city located in the northwest of England. The participating school is located south-southeast of the city centre, in a residential area of the city, and is flanked by a periodically busy road for intra-city traffic. This busy road is hypothesized as a significant source of air pollution exposure for the school staff and pupils, particularly during pick up and drop off times when the roads are busy with pupil's parents' vehicles.

All V2000s were placed away from vents, obstructions, or local point sources to minimise interference (Halsall et al., 2008). The V2000s were placed at a height between 1.0m and 1.68m above floor level to capture the range of heights of pupils at the school, and to simulate child exposure (Rivas et al., 2014). Figure RMS 7.1 shows an aerial shot at 20m resolution of the school with the unit locations. V2000s were installed outdoors (Figure RMS 7.1 (a)), and indoors in the main hall (Figure RMS 7.1 (b)) and in a year 6 classroom (Figure RMS 7.1 (c)).

Figure RMS 7.1: V2000 Unit Locations: a) Outdoors, b) Hall, c) Classroom. School at 20m Resolution.

The outdoor V2000 monitor was also supplemented with a Kestrel 450 to measure meteorological conditions at 1-minute intervals, including temperature, pressure, relative humidity, wind speed, and wind direction, as they have a significant but local effect on UFPs, with higher wind speeds typically reducing UFPs concentrations (Zhu et al., 2002).

Returning to the school where I did my air quality measurements, the teacher agreed for me to visit the school to learn more about its existing materiality and where the V2000 monitors would reside: an array of classrooms, social areas, and outdoor spaces were examined to determine their suitability. For the V2000s' enrolment into the school to be successful it was pivotal that they quickly became an intermediary that would not disrupt the existing school assemblage. To minimise the potential for any disruption, I negotiated on the V2000s' behalf to ensure that they would agree with the existing materiality of the school, its pupils, and teachers. While RMS 7 illustrates and justifies the final locations of the V2000s – the teacher's classroom, the main hall, and directly outside of the main hall – it obscures some of the other machinations at work in deciding their locations.

Air quality monitors designed for indoors and outdoors tend to have different technical specifications. Outdoor air quality monitors are more robust to cover the range of environmental conditions they are subjected to (e.g. rain and more extreme temperatures), whereas those for indoors must be quieter so that they can slip away into the background and measure the air uninterrupted. The V2000 was designed to measure the air indoors and was therefore not designed to cover the range of environmental conditions experienced outdoors, importantly including rain. Therefore, the V2000 preferred to be located indoors, especially since Lancaster has a tendency towards a lot of rain. 'Exogenous' factors such as the wind and the rain were attempted to be dealt with, as detailed in RMS 7 through making auxiliary measurements of wind speed and direction to assist data interpretation of where the UFPs might be coming from. However, an ANT approach would not consider the atmospheric environment to be exogenous at all. Instead, it is "both an actor as well as a network" (Cupples, 2009: 213): an actor that is intimately linked to other social and natural entities and processes (Walker, Booker, & Young, 2022) and a network that can be modelled, quantified, and categorised by atmospheric scientists (Cupples, 2009). Indeed, the wind and rain did affect how the experiment was carried out, owing to its relationship to the specific waterproof limitations of the V2000s. This left the research at the mercy of the weather forecast. To begin the week the weather forecast had looked favourable, but, in typical Lancaster fashion, heavy rain on the final day of measurements prevented me from making outdoor measurements using the V2000. This of course limited what we would be able to say about the dynamics between indoor and outdoor air quality.

Alongside differences between indoor and outdoor air quality monitors, there are also significant differences between instruments that measure different pollutants, owing to the array of other technical devices that are required for them to operate. Some monitors require pumps, others passively detect air pollution. Some can be run using batteries, others require mains electrical connection (if they have energy intensive components, such as pumps). The V2000 is an active monitoring device, which means that it pumps air into the device to be measured. Subsequently, it is powered through a mains electrical connection, which immediately defines where the V2000 can and cannot go based on the location of plug sockets. This electrical connection also had to be out of reach of the children for safety reasons, to minimise their potential interference, as well as in a location to satisfy air quality measurement criteria. Here children emerge as a potential disrupter to the necessary stability of the network. Moreover, it highlights how the location rationalities of the placement of air quality monitors is not always complementary. Whitehead (2009) illustrates this with the case of the deposit gauges, a device used to measure deposited PM: the devices had to be placed in locations where they could best measure pollution events that would affect urban populations, but also in secure locations that would not be tampered with. This contrasting logic also affected my placement of the V2000s: I wanted both to measure the circulating air free from obstructions while at the same time make sure that the V2000 did not look too out-of-place as to disturb the children and warrant any undue attention. A logic, that despite my best intentions was not always successful, with one of the units being turned off during the evening (see Figure 4.13).

Unit 211 was not on when I returned in the morning. Maybe had been turned off? Cable looked a bit loose!

Figure 4.13: Field notes detailing some of the travails of air quality monitoring research.

These material boundaries around access to electrical power intersected with other network relations. In scoping for an ideal location to place the outdoor V2000, there was some deliberation about measuring the outdoor air quality in the school playground (broadly west-southwest of the outdoor V2000 – see Figure RMS 7.1 (a)) given that this is where children spent most of their time outdoors during school hours. Notwithstanding that it was not technically feasible to locate the V2000 outdoors at a large distance from an available power socket, this outdoors also did not represent the outdoor air that I wanted to translate in this research, namely outdoor air quality as the result of traffic emissions during school pick up and drop off times. Both the topography of the area (the school building acting as a barrier) and the relative distance from the road would likely inhibit the enrolment of the UFPs. With the playground designated unsuitable, the front of the school was chosen as the UFPs were more likely to be successfully enrolled. This highlights the agency of the UFPs in determining the location of the outdoor V2000 device, as they would resist enrolment if not measured in the right places.

While these non-human relations strongly influenced the ultimate location of the V2000s, they did not act alone. Nothing ever does. In this research my Lancaster University identity strongly impinged on these enrolments. This research was primarily done to fulfil requirements to gain a PhD at Lancaster University, so it is not particularly surprising that this identity came to bear upon multiple locational decisions that were made during the scoping visit. Notwithstanding the fact that I clearly portrayed certain value judgments about children being undeserving polluted subjects (in the EJ framing outlined in RMS 1), which led IAQ monitors to be placed in schools, this identity also influenced where the IAQ monitors were placed within schools. On the scoping visit there were plenty of classrooms that were possibilities for measuring indoors, including those located towards the back of the school, further from the road (broadly southwest of the outdoor V2000 – see Figure RMS 7.1 (a)). However, as mentioned above, these were far less likely to see much ingress of outdoor air pollution, which would run contrary to the expectation of novel results for getting a PhD. Therefore, looking at indoor and outdoor air quality I wanted to see areas with the potential for high air pollution concentrations in the classroom to demonstrate a potential injustice. Anecdotally this is something that reflects the many discussions I have had with air quality scientists, where we implicitly search for potentially polluted places to deploy our air quality monitors. We have a cognitive dissonance whereby we are simultaneously excited to unearth dangerous concentrations and concerned of its potential impacts.

Other humans and their network relations also played a significant role in determining the locations of the V2000s, with the teacher enrolled into the study especially important. The V2000 locations were determined primarily in discussion with the teacher. Indeed, one of the indoor locations was chosen as the teacher's classroom as it met the required measurement criteria, but perhaps more importantly it was politically easy as it did not require the input of any of the other teachers. That is not to say that other humans were not involved in discussing suitable locations for other V2000s. For instance, the Site Supervisor made it clear that it was more than just the materiality of the school that should drive the location of the V2000s, raising security concerns over the school's experience with the surrounding area. This concern came from my suggestion to install the outdoor and hall monitor indoors together, with a sample line through the window for the outdoor monitoring to sample the air. I made this suggestion partly to play to the strengths of the V2000's technical capabilities but also undoubtedly driven by my Lancaster University and NAQTS identities, which wanted to ensure that the V2000s were placed in locations that would get me good data for my PhD *and* showcase the V2000 in a good light. Unfortunately, it was made clear to me that this was not advisable due to their previous experiences of theft when windows had been left open. Especially as the V2000 is an expensive item and looks like a speaker (which is an attractive item to steal!). In the end it was decided the outdoor unit would be placed outside of the hall during the day where it would be able to enrol UFPs, and I could drape a power cord through the already open window. At the end of every day the outdoor unit would be brought inside for security and weatherproofing reasons. Subsequently, the final indoor unit was placed in the main hall because it was directly inside from the main road, which made an indoor/outdoor comparison most feasible.

Enrolling the V2000s into this school assemblage required me to negotiate on their behalf to ensure that they would agree with their own material strengths and weaknesses, the existing materiality of the school, its pupils and teachers, and the school's relationship and experience with the surrounding area. While RMS 7 does provide a clear locational rationale for the V2000s, and some of these additional rationales may seem trivial and a part of the typical practical issues that all measurement science in the real-world goes through, I bring them to light because they illustrate how typically accounted for things can influence the sort of science that is set up. The location of a power socket can determine where the air quality in a room is measured and ultimately how that indoor space is materialised in terms of air quality. What science is done – and conversely left undone – is influenced by existing networks, in this case my supervisor and his spouse with the school, and my PhD researcher identity at Lancaster University. Moreover, what counts as outdoor can be defined by the research question, technical considerations, but also the school's relationship with the local area.

4.7. Ordering the air

After a week the V2000s were collected and brought back to the laboratory. Untethered from their real-world anchoring, I downloaded the data from them and began to make the air quality perceptible. The air quality representations in RMS 2 provide a routine account of when and where measured concentrations of UFPs were higher or lower. However, there is a last set of steps that I had to take before getting to this final representation of the air: processing the collected 'raw' data into their final form. Here a difference in language between that of natural and social science is evident: raw in natural science designates that it has not been altered since data collection. However, for the social sciences raw does not designate an untouched and natural representation of the world, because raw data is an "oxymoron" (Bowker, 2005): data always comes from somewhere. As I have said above, there is always a model. Indeed, if raw data really was a pure representation of the natural world, we could travel straight from matter to form simply through gathering data. Before getting to the final representations of the air, first the data would need to be filtered, represented, and related: it is these translations that I turn to now.

4.7.1. Filtering the air

The first steps in ordering my data were to filter the data. This involved both taking only the data that was required to answer my research question, as well as removing any errors from the data. Weber (2021: 179) argues that "data production is primarily based not on data collection but on processes that attempt to reduce data quantity and improve data quality." In terms of data quantity, despite being a relatively short air quality monitoring project I collected towards one million data points: enough data to drown in. Filtering the data therefore involved only selecting the data that would serve to address the research question: when and where the air pollution exposure pathways are greatest for school children during the school day? Therefore, all data outside of school hours was removed. In a sense, I had already pre-filtered the air by making my measurements during the school week. However, the air was filtered again to select this time window to cover the school pick up and drop off, plus any after-school activities (RMS 8).

RMS 8: Sampling and Analysis – time periods

Particle Number Concentration (PNC) measurements were made at three locations at the school over a five-day period during July 2018. Data was split into three distinct time periods: drop off, school hours, and pick up. Different age groups had staggered starting and ending times, meaning there were multiple times for the start and end of the school day. As such, the time windows were selected based on the following criteria: drop off (08:20 – 08:45) is based on 20 minutes before the school's first class, and the time that the school gate closes for the latest first class in the morning; school hours (08:40 – 15:10) is based on start of the school's first class, and the school's last lesson of the day; and pick up (14:50 –

15:30) is based on 10 minutes before the earliest last class of the day, and 20 minutes after the school's last class of the day.

While this omittance is referenced in the air quality science account of the research (RMS 8), it does obscure some important considerations. For example, air pollution exposures do happen outside of the selected hours for people at school, such as the high concentrations of secondary UFPs that have been shown to occur during chemical reactions from the use of cleaning products (Reche et al., 2014), primarily affecting cleaning staff. Through this filtering of the air, I focused on some exposures over others (pupils over staff) and, subsequently, some particles over others (primary over secondary). Moreover, the filtering of time periods around pick up and drop off do represent somewhat of an arbitrary cut off. I illustrate this in Figure 4.14 where I contrast the PNC concentrations from the pick up period in Figure RMS 2.1 (Figure 4.14 (A)) with a slightly different time window (Figure 4.14 (B)). For Figure RMS 2.1, I justify the time window through selecting what is deemed as an appropriate length of time before and after lessons start and end (RMS 8). However, in Figure 4.14 (B) I chose a time window that equally could be deemed as appropriate: it covers the earliest last class of the day, and the end of the latest last class of the day (starting 10 minutes later and ending 20 minutes earlier than Figure 4.14 (A)).

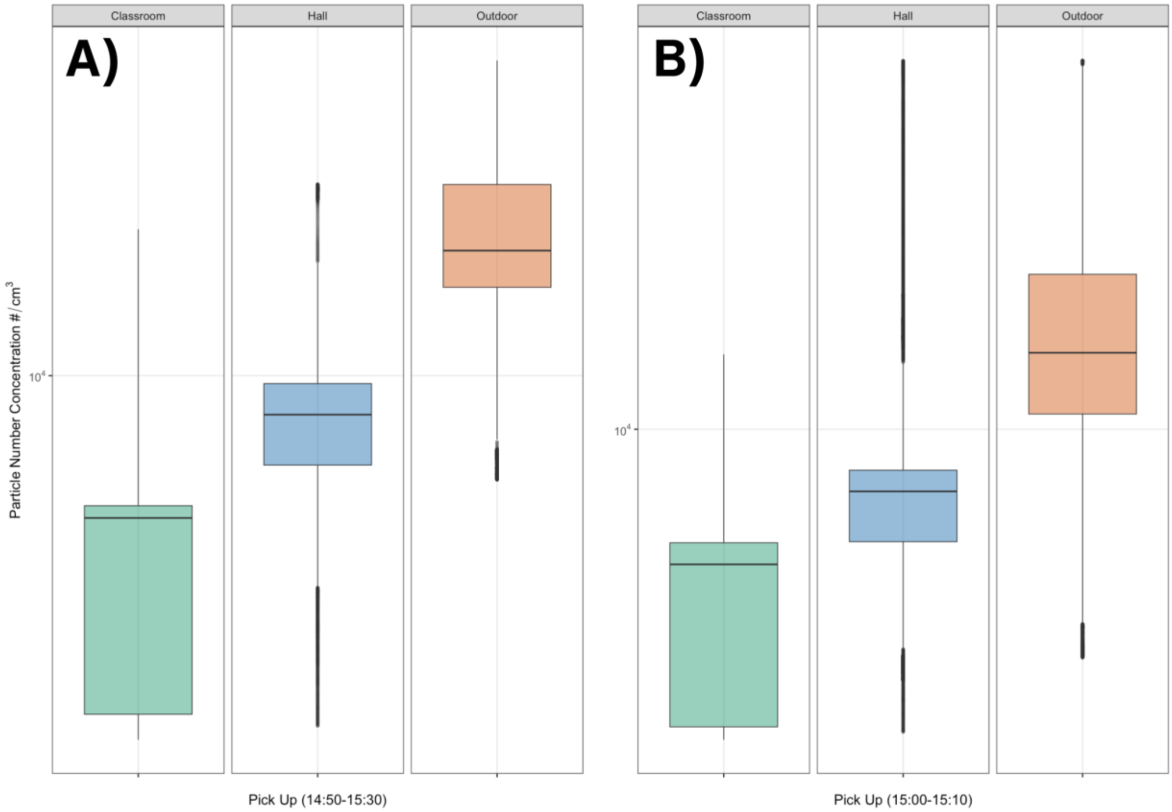

Figure 4.14: The effect of choosing different pick up times on the air quality representations. Figure A) Time window from Figure RMS 2.1, Figure B) Different time window.

While the same overall trend is shown (PNC decreases with distance from the road), which might seem to make it an insignificant change, when interpreting the results across all of the time windows (as shown in Figure 4.15), the story changes: there is no longer a PNC increase in all locations throughout the day. Instead, now the school hours period has a greater mean PNC (in the hall and outdoors) than the drop off period.

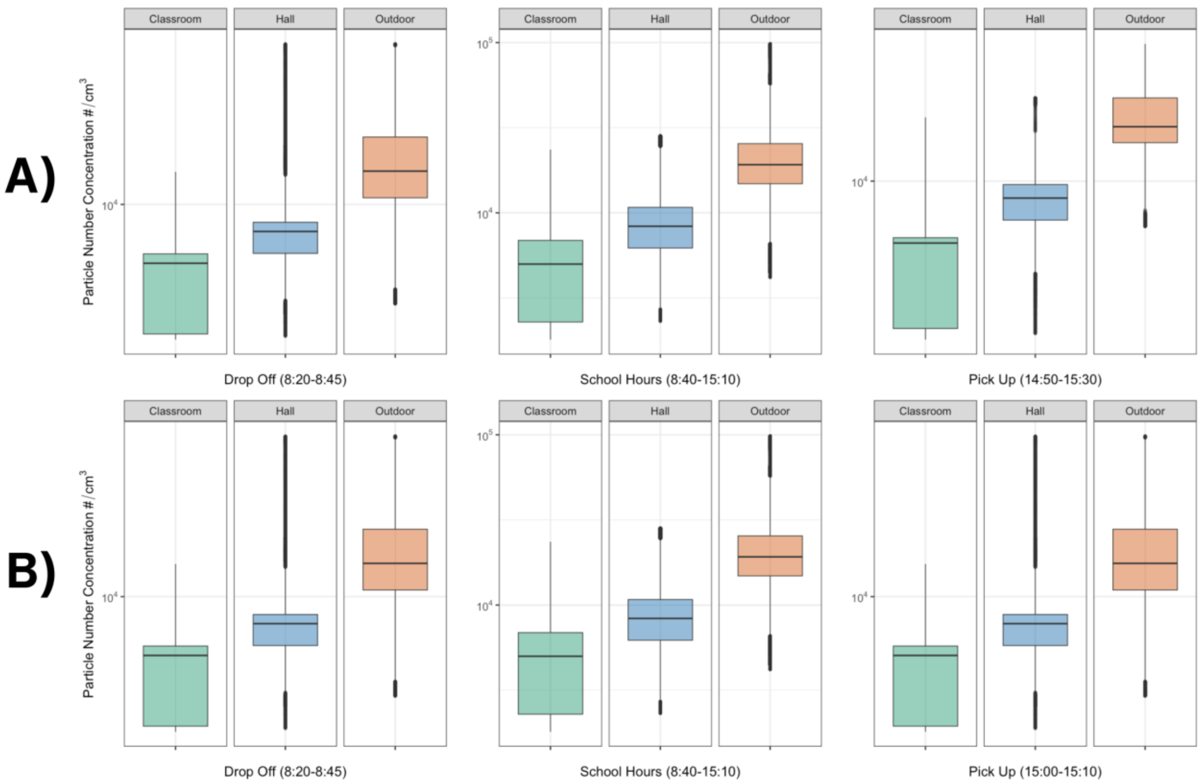

Figure 4.15: The effect of choosing different pick up times on data interpretation and analysis. A) Displays the time windows used for Figure RMS 2.1 B) Displays the same data as A), apart from including the pick up time windows from Figure 4.14 B).

The significance – or insignificance – of this difference is not the point that I am making here. Instead, this difference highlights the unavoidable representational mediation of the air, in this case through imposing temporal order on the data. Making a more universal time period to represent pick up times does allow better compatibility of the results. At the same time, it does lead to the loss of any local peculiarities related to the socio-temporal structure of mobility in the Lancaster area. Moreover, perhaps more importantly, this translation does affect the observed PNC in these time periods, and therefore the final representations of the air. That is not to say that these time windows could not be refined with increased precision and differentiation to better represent when traffic is outside of the school; for example, through including traffic counting to have a dynamic time window. However, this does illustrate science is situated and partial: while science opens some blackboxes, it leaves many others firmly shut.

RMS 9: Data QA/QC
Only data that covered the period when students were typically present (between 8:20am to 3:30pm) were selected in order to not underestimate UFPs concentrations (Reche et al., 2014; Slezakova et al., 2019), and to focus on potential traffic related contributions. Erroneous data were identified and removed using the V2000s in-built error codes. On top of this, the PNC time series for each V2000 was visually inspected and any rapid and/or uncharacteristic changes were reviewed, as per method outlined by Mazaheri et al. (2016; supplementary information). Data availability was ~73% due to a combination of unfavourable meteorological conditions and operational challenges with the V2000 CPC, including a pump that failed.

After reducing the data quantity, the next step was about the data quality, and making the data error free. As Garnett (2017: 909) puts it, "[…] for these numbers to be turned into data, the numerical readings are checked to ensure they are measuring the 'right relations' of air and have not been unduly influenced by the instrument used." I mention these procedures in RMS 9. Data filtering in air quality science tends to be inversely proportional to the ease by which data was collected: when air quality data is collected without any hitches it is scarcely mentioned, when the air quality monitor emerges from the background of measuring the air in the classroom and becomes a mediator through the breaking down of a device such as a pump, it figures much more strongly. In part, this selective focus is to strengthen the claims that can be made about the data, so that any data that is removed because it is not measuring the right relations does not make the rest of the data conspicuous by its absence. For example, Salami et al. (2013) wrote at length of the challenges they had measuring UFPs, due to a design flaw in the CPC they were using. The problems were significant enough that they discussed extensively with the manufacturer and the production of this CPC was later discontinued, which they speculate possibly being related to their issues.

As mentioned in RMS 9, the V2000 assisted our filtering of the air through a series of inbuilt error codes (of course these were programmed by its inventors!) to notify the user when a flow, temperature, voltage, or another component might have gone awry. However, despite its participation in an established metrological regime (RMS 5), at this stage the V2000 was still an assemblage that was stabilising, with this project an early trial of its strength in measuring the air in this real-world setting. Thus, while these error codes did provide an easy way to filter the data for quality, they did not resolve all the peculiarities of the data that was generated. In fact, there were multiple points during the monitoring window where the data did not look sensible, and it was not always immediately clear why. As I previously mentioned, every day I would visit the school to move the outdoor unit indoors overnight. During this visit I would check on the status of the V2000s through quickly downloading and analysing the data. I mention in in RMS 9 that I would visually inspect the time series of the data. Figure 4.16 is an example of this, where I analysed the data that been collected during the 2nd day of the deployment in the classroom. Both the shape of the PNC time series, and the absolute concentrations were red flags that the V2000 was not measuring the right relations.

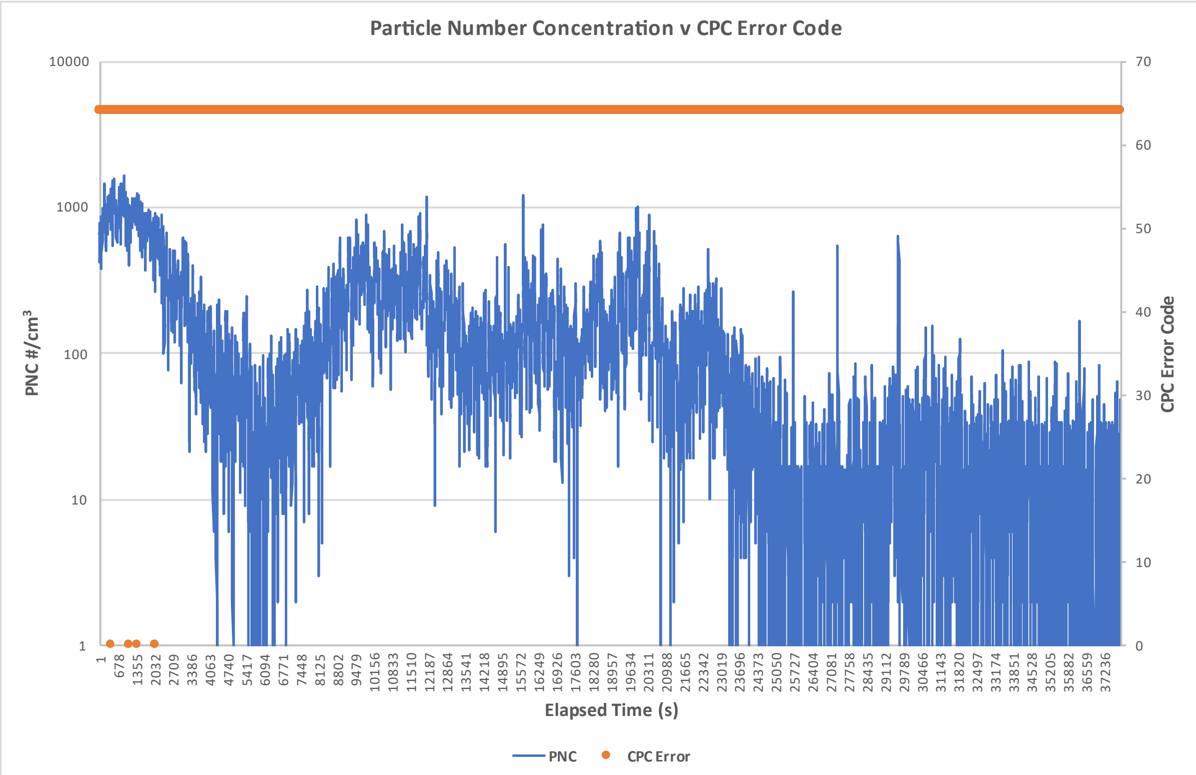

Figure 4.16: Interrogating some erroneous PNC data by looking at the NAQTS V2000's in-built Condensation Particle Counter error codes.

This representation did not pass the 'laugh test', a phrase I came to learn of by working closely with my father, David: a scientist should be able to report their results as legitimate without the compulsion to laugh. In my case, this was not possible as typical indoor PNC are in the range of 1000–10,000 particles per cubic centimetre. In Figure 4.16, the concentrations are substantially less (and going to zero), which, if correct, would suggest I was measuring UFPs in a hermetically sealed box containing a HEPA filter – something that was clearly not the case. Moreover, the shape of the curve, especially from ~25,000 seconds onwards, is much 'noisier' than I would expect to see in an environment without a significant indoor source of UFPs.

In my attempt to explain these irregularities, I turned to the V2000's in-built error codes. Figure 4.16 shows the error code '64' was prevalent throughout the monitoring period, indicating that the pump pressure for the CPC was outside of its optimum operational range. For someone who is not as well attuned to the V2000 as I am, this might be enough to discard the data. However, I knew that it was only *slightly* outside of its operating range, as it had been consistently across the other days when it had been a stable assemblage and its data were good. Subsequently, my filtering of the data did involve drawing upon my feeling for when it might be erroneous (Garnett, 2016). Given my inside knowledge of the instrument, I know acutely when the device is – or is not – within its appropriate bounds. In this case, I knew that it was likely due to blockages in some of the flow paths that could be resolved by taking the V2000 back to the laboratory to give its internals a literal clean. Therefore, sometimes data could be kept even when they had error codes attributed to them (as had been in other days when the pump was slightly outside of its ideal operating range). However, on other occasions problems with the data were unearthed from my own embodied feeling for error (Garnett, 2016). Therefore, while RMS 9 provides a logic for ensuring data quality, it is a much more ordered and stabilised account of what actually happened, despite including interpretively flexible phrases such as the of reviewing "uncharacteristic changes."

4.7.2. Representing the air: filtering, uniforming, upgrading, and defining

With a filtered dataset, the next step of ordering my data was putting it into material inscriptions that would be suitable for the pages of a scientific journal, allowing the measurements I made indoors and outdoors to move more easily from place to place. Lynch (1990) outlines four ways that representations are transformed to facilitate this mobility: filtering, uniforming, upgrading, and defining. I use these methods as a heuristic to explain the processes that I went through to represent the air that I measured.

This filtering is not to be confused with the filtering earlier on, which were processes about reducing data quantity and increasing data quality. Instead, it is about changing the characteristics of the representation: Lynch (1990: 209) refers to filtering as the process of representations being produced to "exhibit a limited range of visible qualities." This filtering was an important part of generating the inscriptions shown in RMS 2. The liveliness of UFPs, and their resistance to being transformed into inscriptions represented a challenge. UFPs are much spikier in their appearance and disappearance than other air pollutants due to their sociomaterial dynamism: being primarily from a dynamic source (i.e. traffic), but also highly dynamic in their atmospheric transformation. The filtering in this case was then related to exhibiting only a limited number of the UFPs, through finding an appropriate averaging time. The limited way in which this information is normally provided is shown in RMS 10.

RMS 10: PNC Averaging Period

A range of different averaging periods have been used for looking at indoor and outdoor UFPs concentrations including; 30s (Salimi et al., 2013), 1 minute (Slezakova et al., 2019), 10 minute (Reche et al., 2014), 15 minutes (Diapouli et al., 2007), and 1 hour (Mazaheri et al., 2016). In this study we used a 10 minute average, to focus on shorter-term exposures.

UFPs were measured second by second. However, presenting it in this way was not especially useful, as it is too hard to visually decipher the signal from the noise, in part due to the clear connection to individual vehicles' UFPs, which would result in a momentary large spike. My research was not about the role of individual vehicles; instead, it was about the role of socio-temporal structures such as the pick up and drop off times around schools. Subsequently, the visual representation of second-by-second data emphasizes the wrong relations to the air that I was investigating. In the end, data was truncated to 10 minute rolling averages, as a sort of happy medium that would both represent short term exposures, but not be dominated by individual polluting vehicles. While RMS 10 does not directly use the language of a "happy medium" it does present it in this way, through selectively presenting two shorter and longer time periods as alternatives. The difference visualisations that come from choosing different averaging period is shown in Figure 4.17, where the curves are different shapes, and the peak concentrations are even different. These differences are reminiscent of Ottinger's (2010) work, which investigated government regulator and activist use of air quality data to make claims of harm. Regulators tend to produce average concentrations over longer periods of time to compare to air quality standards, whereas activists focused on short-term spikes to demonstrate the air was unsafe. While both are representations of the air, they embody different relations to the air, including sources and claims of potential harm.

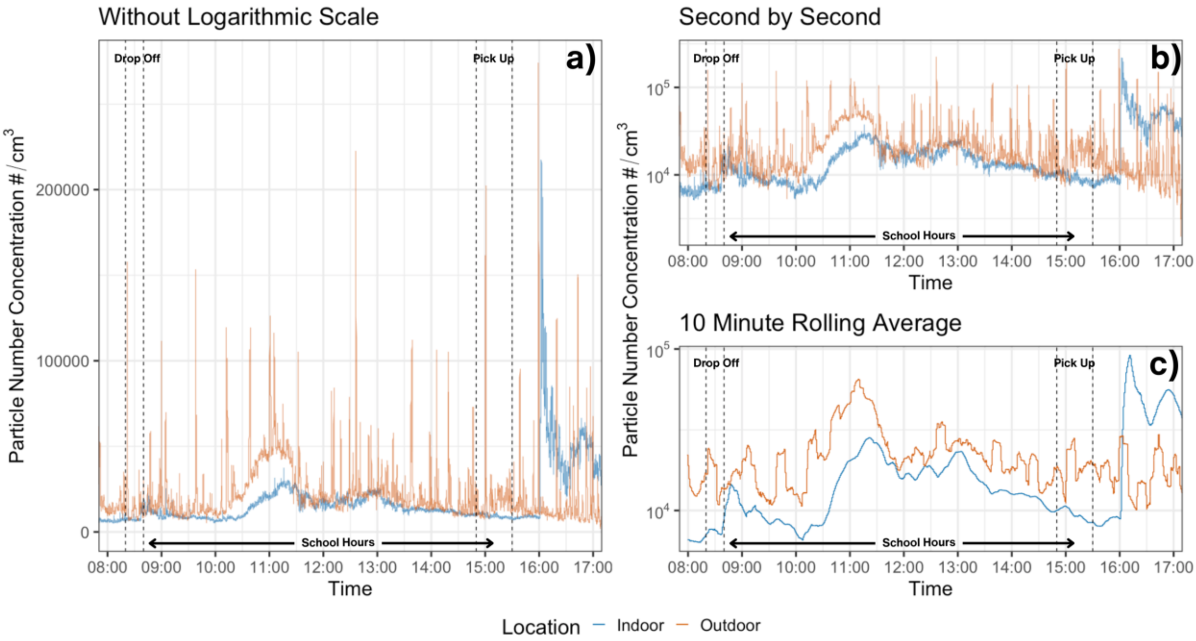

Figure 4.17: Transforming the data through filtering, uniforming, and upgrading. Figure a) Data presented on a linear scale, Figure b) Data presented on a logarithmic scale with no averaging, Figure c) Data presented on a logarithmic scale with 10 minutes averaging.

Figure 4.17 also shows the process of uniforming the data to make them look more like one another. UFPs can change by orders of magnitude in their concentration over seconds when a polluting source is nearby, which confounds some of the normal ways of visualising air quality data. This uniforming was achieved in two main ways: first, using a logarithmic scale for the particle count and second, by performing temporal averaging (Figures 4.17 (b) and (c)). Visually, analysing the data on a linear (Figure 4.17 (a)), rather than logarithmic, scale is difficult, as the eye is drawn to large spikes rather than trends. Likewise, the indoor and outdoor locations would be very different on a linear scale, given the one large, sustained peak indoors at around 4pm. Similarly, averaging across all days facilitates the identification of trends rather than the day-to-day variability, albeit at the expense of obscuring individual peaks on a given day.

Moreover, the representations were upgraded to make the UFPs “more congruent with the identities assigned to those entities” (Lynch, 1990: 106). This included adding coloured lines to show both monitoring locations and vertical dashed lines to show the pickup and drop off periods. The representations were also defined not just to make them “more like one another” but also so that “they are more clearly distinguished from unlike entities” (Lynch, 1990: 209). This was done for the boxplot (see Figure RMS 2.1) where the data were presented in such a way as to allow for easier comparison of the range of concentrations across different period of days.

4.7.3. Relating the air

The final step of ordering the data is relating it to other studies. I do this in RMS 11, where I include an excerpt of a table (Table RMS 11.1) that compares gathered results to those of other studies. The UFPs that I measured only come to count as anything when they are related to somewhere else, or at another point in time. The same can be said of other pollutants that gain agency through their relation to other measurements, regulations, or legal limits. What comes to count as good or bad air quality depends on these relations. One of the challenges in making the comparison for UFPs is the non-standardised way in which they are measured, especially related to the different cut-off sizes of CPCs. This means that while CPCs all measure the number of particles in the air, different CPCs will report very different absolute numbers. The way in which this information is normally provided is shown in RMS 11, recognising that the lack of a “structured envelope” (Law, 1984) around UFPs measurement – that is, the social, technical, and political context that allows or inhibits the movement and durability of actants – inhibits them from becoming immutable mobiles through comparison of results across studies (USEPA, 2019). However, calls have been made for CPC cut-off points to be standardised to permit comparison (e.g. Lowther et al., 2019). Moreover, centres of calculation are starting to develop: the World Health Organization (WHO) has, for the first time, outlined good practice statements on UFPs to “guide national and regional authorities and research towards measures to reduce ambient ultrafine particle concentrations” (WHO, 2021: 150). This includes suggested size ranges, and hourly and daily averages that can be considered high or low.

RMS 11: Results 2

Indoor/Outdoor (I/O) ratios were somewhat comparable to previously published results looking at PNC in schools (see Table RMS 11.1). However, for the absolute PNC please note that the summarized studies reported PNC of various size ranges (N7.6-1000nm), which limits the comparability of the results.

Table RMS 11.1: Summary of previous studies reporting Indoor/Outdoor PNC in schools.

Place of study	Period of study	Study description	Size range measured and reported metrics	Reference
Athens, Greece	November 2003 – February 2004 October – December 2004	7 schools 2-5 days per school	N10-1000nm (8h mean): 24,000 ± 17900 indoor 32,000 ± 14,2000 outdoor I/O ratio 0.33 – 0.74	(Diapouli et al., 2008)
Porto, Portugal	January – April 2014 October 2014 – February 2015	20 schools, 73 classrooms 5 days per school	N20-1000nm (median): 1560 – 16,800 indoor 1790 – 24,100 outdoor I/O ratio 0.3 – 0.85	(Slezakova et al., 2019)
Brisbane, Australia	February 2006	1 school 10 days	N15-790nm (mean): 3190 ± 263 indoor 2650 ± 152 outdoor	(Guo et al., 2010)
Barcelona, Spain	January – June 2012 September 2012 – February 2013	36 schools 4 days per school	N10-700nm (mean): 15,577 ± 6586 indoor 23,396 ± 9986 outdoor	(Reche et al., 2014)
Texas, USA	February 2009 – 2010	5 schools 3-8 days per school	N7.6-100nm (geometric mean): 600 – 29,300 indoor 1600 – 16,000 outdoor I/O ratio 0.12 – 0.66	(Zhang and Zhu, 2012)

For many air quality applications there are generally applicable methodological rules for ordering the air. For example, Garnett (2016) examined the data practices of an air quality expert responsible for maintaining the UK Government's Automatic Urban and Rural Network (AURN) monitoring stations: while their data filtering procedures were governed by standard operating procedures set by UK and EU legislation, work still had to be done to make them fit for that context. This involved "carefully balancing the context of measurement, the phenomena under study and their ability to effect and affect air pollution as a research object" (Garnett, 2016: 9). This highlights air quality data as a local achievement, which is often obscured in published scientific work (Sismondo, 2010). It is often said that measured air quality data is trusted by others more than by those who generate the data. Perhaps that is because the inscriptions created by air quality measurements are carefully tailored to present ordered network interactions, whether that be through filtering, uniforming, upgrading, or defining. In doing so, it obscures its locality, the fixing of instruments, and the tacit knowledge required to make air quality data.

4.8. From (Particulate) Matter to Form

So far, I have traced all the actants that have influenced how this air quality science was set up and carried out. In this section, I draw upon Latour's (1999) concept of circulating reference to outline the transformations that I went through to go from the material air to the ultimate meaning of it that generated and stabilized in my representations (RMS 2). This was not through "the face-to-face confrontation of a mind with an object" (Latour, 1999: 69); rather, it was through a series of transformations that PM was translated into more mobile forms that could also be reversed assuring "a pathway back to the dust" (Choy, 2012: 31). I show these transformations in Figure 4.18, detailing how through each stage of the research I "lost locality, particularity, materiality, multiplicity, and continuity" but simultaneously gained "much greater compatibility, standardization, text, calculation, circulation, and relative universality" (Latour, 1999: 70). The sequence of stages of the research are illustrated by numbers on Figure 4.18.

The matter that I chose to begin my circulating reference with is the air. Ultimately this is what I wished to represent when answering my research question of when and where the air pollution exposure pathways are greatest for school children during the school day. For my research – and in fact in any air quality science research! – measuring the air in its totality is an impossible endeavour. The first step was to choose particulate matter (PM) as a material constituent of the air to pursue (Figure 4.18 – 1). As I have already argued, there is no one PM: PM is multiple. It is stable enough that the category of PM even exists, but disparate enough that there are a variety of metrics that are deployed to understand it. Subsequently the next link in my chain was focusing on ultrafine particles (UFPs) (Figure 4.18 – 2). These initial transformations have already reduced the air substantially: it is no longer an indefinable, all encompassing, and multiple entity. Through a series of transformations, the air became PM with a diameter less than 100nm.

With the air represented by UFPs, it was then further transformed by enrolling the NAQTS V2000. This transformed – and justified that transformation – UFPs as a metric into a measured particle number concentration (PNC) (Figure 4.18 – 3). While at this stage we have lost any instance of what the particle was made of, wherever it came from, or indeed its size, it is this reduction that allows PNC to travel more freely across the scientific texts of articles, allowing comparisons across other locations and across time.

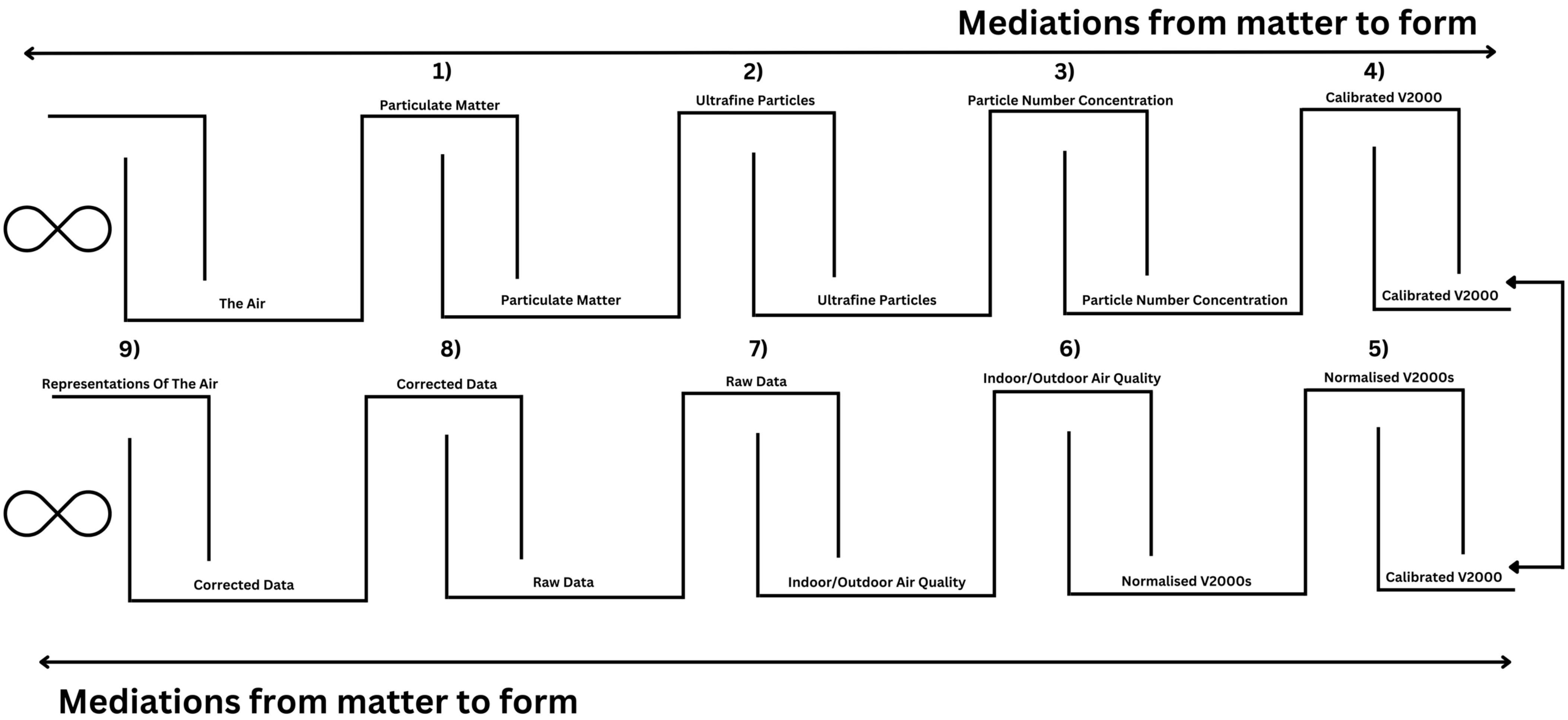

Figure 4.18: The circulating reference for my air quality monitoring project, detailing the stages I went through to go from the air to the representations of it in RMS 2. The numbers above each step illustrate their position in the sequence.

This counting of particles is a delicate procedure, and the next step in my chain was to take the V2000 and its capability to measure and report PNC and metrologically validate it through enrolling ISO-27891 (Figure 4.18 – 4). At this stage a range of different actants were enrolled, from other scientific instruments, to standard operating procedures, to air quality consultants. Here we moved away from the messy air of the real-world and instead brought in a manufactured air in the form of calibration aerosols. Here the air was further reduced to particles of a standardised material and size at a certain concentration, to create a calibrated V2000. However, through this reduction I also gained far greater compatibility and standardization, as in principle this condensation particle counter (CPC) would see the same number of particles in a volume of air as any other CPC: this would permit comparisons across space and time of the data that would later be generated.

With a stablished method of counting airborne particles, I then used this literal reference air quality monitor to normalise the other V2000 devices to make them agree on how many particles they were seeing at a given time (Figure 4.18 – 5). This standardisation of V2000 devices was a key step to permit the circulation and relative universality of the forms that would later be made: it is the normalised V2000s that allow for the comparative indoor and outdoor air quality to be materialised (Figure 4.18 – 6). Following both the air quality science placement logics, and the specific sociomaterial limitations of the school, these air quality measurements would go on to represent the air indoors and outdoors at the school. In doing so, the specificities of these indoor and outdoor locations – including the account I have in earlier outlined in the main body related to determining their locations – became black boxed and stabilised in the form of indoor and outdoor air quality: a universal indoors and outdoors that could be anywhere at any time.

The next step in the chain that I outlined was the transformation of the air indoors and outdoors into nearly one million raw data points (Figure 4.18 – 7). These numerical representations of the air bring us much closer to the final representations in RMS 2. However, it is after I transformed the raw data into the corrected data through filtering to reduce data quantity and improve data quality that I could make sure that I was measuring the right relations (Figure 4.18 – 8).

The final steps were to represent the air through transforming the corrected data through a process of filtering, uniforming, upgrading, and defining, before relating my measurements to the literature (Figure 4.18 – 9). For Latour (1999: 70–71) this circulating reference meant that by the end of his collaboration, in their report they "hold not only all of Boa Vista (to which we can return), but also the explanation of its dynamic." For me, by the of this paper, I hold all of the air indoors and outdoors at this school (and the explanation of its dynamic), to which I can return through a series of steps (despite the air having long left my V2000!): we have come very far from the change in a voltage of a photodiode to representing the air indoors and outdoors at a school in Lancaster.

4.9. The – right? – role of air quality science

Throughout this paper I have shown the important role that I – as an air quality scientist – played as the network translator in mediating a relationship with the air. These mediations occurred at all different stages of the research, including choosing what and where to measure (and the use of certain monitoring instruments), and how to clean and represent the data. These transformations, or links in my circulating reference (see Figure 4.18), ultimately came to shape our understanding of the air indoors and outdoors at this school. I argue that these mediations have potentially important implications, as by framing the air in a certain way, it dictates how one might respond. In this section I outline how the findings of this paper might be taken up by air quality scientists to promote a more effective and equitable engagement on issues of air pollution. I do so by outlining potential interventions in the process of doing air quality science that relate to the initial framing and reporting of air quality science. Given the necessarily partial perspective that I provided, this of course principally applies to the type of air quality science that I did, namely, a field measurement campaign. There is no one air quality science: some involve measurement by deploying instruments in the 'real-world' or in environments that simulate it, whereas others generate no data at all and simply examine pre-existing datasets such as by modellers. Therefore, how the specific findings apply to different types of air quality science remains an open question. Nonetheless, there are two general messages that I believe are important considerations for all air quality scientists, that involves reflexivity to probe what they are doing and why, and with what sociomaterial effects.

First, through outlining my role in setting up the project, and the range of relational influences on my practices, I present an opportunity for air quality scientists to question the underlying logics of their study more thoroughly including what is being measured and why? For example, in my project I highlighted that the focus on UFPs was both in response to a dearth of scientific information on their concentrations in indoor environments (as highlighted in RMS 1), but also to provide a ’novel’ measurement that would do well for me and my PhD, and for NAQTS by showcasing its main technological offering. For the avoidance of doubt, this is not to say it was wrong in any way for me to have measured UFPs. It is more an honest recounting of the range of factors that influence what is measured in air quality science. I argue, therefore, that it is helpful for scientists to reflect on what is influencing what they decide to measure beyond a simple scientific justification outlined in a literature review, to also include, for example, the influence of funding, and availability of technology. On the why, of course, if one sees the measurement activities of science as a completely neutral activity, one can simply collect their data and then retreat to the University. However, in an academic climate that increasingly demands ‘impact’, including ‘solution-focused’ research that can be transformational and protect public health, air quality science is increasingly public-facing. For example, in my project the aim of producing this knowledge was to provide evidence to support reduced local emissions of UFPs and exposure of vulnerable populations (alongside gathering good data to complete my PhD!). Many air quality research projects implicitly will have a similar framing. However, there may also be research that is more directly aimed at getting back to an imagined “pristine nature” where there was no air pollution, or believing in “the notion of guidelines and safe levels” (Cupples, 2009: 215). The differences in the why here has big implications on visions of what future air quality should look like, and air quality science’s role in moving us towards that future.

The choice of what to measure and why has implications for how one might act. This relates to the second reflection that I recommend for air quality scientists, which is to think through the potential sociomaterial implications of their projects. In my project, through measuring the air by number (rather than by mass), I emphasized local pollution sources, that is, the cars driving directly by the school gates. Therefore, I attributed different responsibilities for their emissions (or clean up). Indeed, this way of knowing the air necessitates a specific set of responses, including a much more localised / personalised intervention, such as encouraging children to walk to school on a less polluted route to minimise their exposure and discouraging parents from dropping kids off at school by car to reduce emissions. Whereas, for example, if I had decided to measure another pollutant such as NO_2, which also primarily derives from traffic but importantly is also regulated, it might move questions of the responsibility of avoidance and reduction in air pollution from the public to those with power locally. Therefore, a more effective (in terms of potentially reducing air pollution concentrations and exposures) and equitable engagement here would be to co-design the study more concretely with those affected, so that it would have better suited their needs. Moreover, it would engage other parts of the system involved in the air quality problem / solution, as those that my study designated as the 'polluted' (i.e. the children) are also somewhat the 'polluter' through being dropped off at school (albeit indirectly as their parents are driving the vehicles). This uncomfortable truth is important for air quality scientists to think through, lest their research have unintended consequences. For example, air quality science might inadvertently end up making things worse by designating an area as 'polluted', further worrying affected people without providing a process for making things better. Moreover, for those who are designated as doing the polluting, in this instance that is the people dropping children off at school or likely commuting to work, we must consider their capability to transition to a less polluting mode of transport. In this case, that would involve thinking about where our work is ultimately placing responsibility: is it on individuals to reduce their polluting activities? Or is it on a system that means that they must do that polluting activity to fulfil their other obligations (e.g. arriving at work on time), in lieu of a public transport system that cannot currently handle their mobility requirements.

4.10. Conclusion

In this paper I have challenged the ordered scientific account of an indoor and outdoor air quality monitoring set out to understand when and where the air pollution exposure pathways are greatest for school children during the school day. Using the concept of circulating reference (Latour, 1999), I have shown that "air pollution like any environmental problem cannot escape representational mediation" (Cupples, 2009: 210). I traced the steps taken to go from (particulate) matter to form, detailing the role of a variety of human and non-human actants that influenced the questions about air quality that the research asked, and how they were investigated, including; the scientific reasons for setting up the project; the technical specifications and operating mechanisms of the air quality monitoring device used (including its calibration and normalisation); the logics for its placement indoors and outdoors; and how air quality data were filtered, represented, and related to create an understanding of when and where the air pollution was greatest. In focusing on these transformations from matter to form, and the role of three main actants (the pollutant that was measured, the air quality monitor that was deployed, and my plural identities), I highlighted relations that are typically obscured in the reporting of air quality science including; my goals and motivations as a PhD Researcher and owner of the business that designed and developed the air quality monitor that was used; how this air quality monitor enrolled some particles better than others; and ultimately why a certain world was made visible. In doing so, I identified important areas for air quality scientists to facilitate a more effective and equitable engagement on issues of air quality by reflecting on their research, including thinking carefully about what they are doing and why, and with what sociomaterial effects.

Shapin (1995) acknowledges that a recognition of the idiosyncratic localised practices that constitute the construction of scientific knowledge may not ultimately prove that a different reality would be constructed under different conditions. For my indoor and outdoor air quality monitoring project, to claim that other factors played an active role in the way that the science was carried out is not to say that the research was not scientifically legitimate. However, it does highlight how they embedded a certain set of relations with the air that ultimately informs our understanding of – and subsequent reaction to – air pollution. In short, the scientific facts – the measured concentration of an air pollutant indoors and outdoors at a school – that were generated cannot be separated from what produced them: me, my air quality monitors, and the air itself.

5. Unstable air: How COVID-19 remade knowing air quality in school classrooms (Paper 2)

Booker, D., Walker, G., &. Young, P.J. Unstable air: How COVID-19 remade knowing air quality in school classrooms. *Ephemera: Theory & Politics in Organization (In press).*

Abstract

Air quality is neither a stable material phenomenon, nor form of knowledge. This was made clear upon the arrival of COVID-19 in school classrooms when humans emerged as the primary source of poor indoor air quality (IAQ), and a host of new devices were placed into schools to monitor and clean IAQ. In this paper we examine this instability as it had consequences within a research-business project attempting to measure IAQ and assess the effectiveness of an air cleaning device in school classrooms pre- and post- the emergence of COVID-19. Using a 'near' Actor-Network Theory analytical framework we focus on how a network of 'science in action' became re-assembled to COVID-19. Drawing on IAQ data that we collected, government and industry statements and reports, and the direct involvement of the lead author using both reflexive and relational ethnographic approaches, we show how our IAQ measurements, combined with other material inscriptions, were powerful actants that changed the relationship between the air indoors and outdoors. We bring Maria Puig de la Bellacasa's concept of 'matters of care' into conversation with the project detailing how changing socio-material circumstances led to a more active role to reconfigure classroom IAQ, and how we might better care for IAQ in the future. We also relate our project to the wider – and ongoing – process of reassembling IAQ, asking how this might relate to questions of inequalities and responsibilities.

5.1. Introduction

Air quality is neither a stable material phenomenon, nor form of knowledge. What constitutes good or bad air seemingly consolidates in maps and graphs of gaseous or particle concentrations, in standards and thresholds, and in ‘metrological regimes’ of measurement and organized governance (Barry, 2002; Calvillo, 2018). However, air quality’s stability is illusory. What is judged to constitute the safe and the harmful, the naturally clean and the human contaminated, is always a cultural matter that shifts over time (Douglas, 1966). For the air of contemporary worlds, developments in scientific knowing of the air and its consequences have been important in repeatedly moving on established understandings, along with innovations in technologies for appraising the air’s constituent elements (Whitehead, 2009). As new material entrants into the air have been encountered where they were not before, and as the meaning and experience of being polluted (Bickerstaff, 2004) has become contested and politicised, investments in knowing, ordering, and organizing the governance of the air have also shifted and evolved. As scholars drawing on perspectives from science and technology studies (STS) have emphasised, the air and the diminishing of its quality is a thoroughly ‘hybrid’ sociomaterial phenomenon (e.g. Clifford and Travis, 2020; Cupples, 2009; Garnett, 2016). Thus, notwithstanding the air materially existing independently of us, “atmospheric scientists produce the air” (Cupples, 2009: 213), but not in a way that ever finally resolves what it is they are producing.

In this paper, we build on this foundation to examine how the air and its qualities became made, known, and organized differently following the arrival of SARS-CoV-2 – the virus that causes COVID-19 – into the atmospheric immersions of breathing bodies. Whilst evidently a truly global experience, we focus here specifically on how COVID-19 entered into a process of knowing and attempting to improve the air for vulnerable bodies that was already underway as the pandemic took hold. We trace how the virus, as a potently agentive actor, reconfigured some core constituent elements of an applied research-business project, both measuring indoor air quality (IAQ) in school classrooms and assessing the effectiveness of air cleaning technology in stripping out elements that had been generated indoors, and / or found their way inside from the outdoors. Using a ‘near Actor-Network Theory’ (near-ANT) analytical framework (Farías et al., 2020: xxii), we focus on how a network of ‘science in action’ (Latour, 1987) became re-assembled to a new and intensely problematic component of the air in-between breathing bodies.

In this paper we investigate the organization of breathing in school classrooms following the emergence of COVID-19, showing how a variety of human and non-humans were enrolled, changing definitions of what constituted good IAQ, and the relationship between the air indoors and outdoors. Moreover, we draw upon the direct involvement of the lead author – who was a key actant involved in the co-production of the materiality produced by the IAQ monitors and its subsequent recasting in practice – using both reflexive (Aull Davies, 2012) and relational (Desmond, 2014; Simon, 2013) ethnographic approaches to show how new ‘matters of air-care’ (Brown et al., 2020; Puig de la Bellacasa, 2011) were enacted as the goals of the research project actors changed. Through looking at our ‘production’ of the air, and its entanglement within a “complex assemblage of people, places, materials and technologies” (Weber, 2021: 181), we interrogate the particular organization of sociotechnical infrastructures that made perceiving and responding to the air possible. We finish by relating our case to the wider reassembling of classroom IAQ and speculating on whether these reconfigured pandemic assemblages are here to stay, and what that might mean for inequalities. We begin by outlining the reason for our focus on the air we breathe indoors, summarising aspects of the natural and social science literatures, as well as the implications of COVID-19 on this domain.

5.2. Literature review: The indoor-outdoor air continuum and the virus

For air quality science, outdoor ‘ambient’ air has long been its primary focus (AQEG, 2022). With increasing precision and differentiation, the emission, circulation, accumulation, and dispersion of pollutants into the atmosphere has been measured, analysed, and modelled, with a particular focus on urban and industrial settings. As a consequence, there is now a considerable body of knowledge (at least for some places) about what outdoor airs are made up of, including how air quality can vary spatially such as street by street (Apte et al., 2017), and change over time with the rhythms of its making and interaction with atmospheric processes (Walker et al., 2022). Much knowledge has also been accumulated on the consequences of breathing in polluted air, the extraordinary number of deaths per year this breathing is implicated in (HEI and IHME, 2020), and who is particularly vulnerable to these consequences. Amongst those deemed the most vulnerable, children figure centrally. Children have been found to be especially susceptible to outdoor air pollution due to a combination of factors (WHO, 2018). Behaviourally, children are more physically active than adults, and therefore have a higher inhalation rate relative to body mass, meaning that they breathe in more air pollution (Royal College of Physicians, 2016). Environmentally, these inhalations occur closer to the ground where outdoor air pollutant concentrations tend to be more concentrated (e.g. Kenagy et al., 2016). Physiologically, children have narrower airway passages that when inflamed have a proportionately greater airway obstruction and can exacerbate existing respiratory conditions such as asthma (Takenoue et al., 2012).

However, breathing clearly happens both outdoors and indoors, and over recent years air quality science has increasingly been focused on indoor air, with attention to what is added to the air by indoor activities and technologies (for example, cooking, wood burners, paints, cleaning products etc.), how polluted outdoor air can get inside buildings and contaminate indoor environments, and the role of ventilation in mediating flows of indoor-outdoor air quality (which is often measured using carbon dioxide, a component of the air to which we later return). These flows are of particular concern for school IAQ research, with a wealth of studies exploring the links between traffic air pollution around schools and school children's health (e.g. An et al., 2021), and cognitive development (e.g. Sunyer et al., 2015). Despite people in Western industrialised countries spending more than 90% of their time indoors (Klepeis et al., 2001), and the potential for personal exposure to be greater indoors rather than outdoors (Vardoulakis, 2009), IAQ science has remained mostly "undone" (Frickel et al., 2010). Notwithstanding a growing interest in the materiality and politics of breathing, including some recent special issues (Kenis and Loopmans, 2022; Oxley and Russell, 2020), the indoor environment remains a comparatively less studied domain. Indeed, Biehler and Simon (2010: 172) have explicitly called for "more attention to indoor environments as active political-ecological spaces" that both engage with the material movement of ecological systems (such as outdoor air pollution drifting through an open window), but also "the assemblage of institutions and individuals vying to control the governance of those systems” (Biehler and Simon, 2010: 186). There have been some notable contributions in this space, including those focused on key themes to investigate in the urban indoors (Graham, 2015), on different modes of knowing the air indoors (Altman et al., 2008; Garnett, 2020; Shapiro, 2015), and on how uncertainty is politically weaponised (Grandia, 2020; Murphy, 2006). The intersection of STS and organization studies is beginning to be examined for outdoor air quality, such as by Weber (2021) who looks at how the air outdoors is perceived through organized physical, chemical, and informational filters to create data. However, we can also bring these investigations indoors, outlining the processes and practices that shape sociomaterial relations within buildings.

The arrival of COVID-19 had consequences for both outdoor and IAQ. Outdoors was generally seen as a safer place for breathing in terms of viral transmission, but the impact of lockdown rules on emissions from traffic and industry precipitated the largest ever air pollution ‘natural experiment.’ Lockdowns and work from home directives led to drastic reductions in emissions from traffic and industrial sources (Doumbia et al., 2021), and, depending on the local weather (Matthias et al., 2021), and atmospheric composition (Kroll et al., 2020), reduced gaseous and particle concentrations in many locations (Rodríguez-Urrego and Rodríguez-Urrego, 2020; Venter et al., 2020). For the indoors, work from home directives (for those that could do so) are hypothesized to have increased residential indoor air pollution (Adam et al., 2021), including from new social practices around ‘hygiene theatre’ (Kale, 2021), which increased the use of surface disinfectants and hand sanitisers which exacerbated concentrations of certain volatile organic compounds (VOCs) indoors. More fundamentally though, viral transmission risks through the air in indoor environments became the object of intense attention, uncertainty, and controversy, with different scientific definitions of what constitutes ‘airborne’ (Randall et al., 2021), and focuses on different particle sizes, namely droplets or aerosols (Jimenez et al., 2022). In schools specifically, this led to the prioritisation of a host of different classrooms interventions, with proponents of droplet transmission favouring surface disinfection and lateral plexiglass barriers, versus aerosol transmission advocating for a ‘paradigm shift’ to increase ventilation rates through behavioural modifications (e.g. window opening) and mechanical technologies (e.g. heating, ventilation, and air conditioning [HVAC] systems, and air cleaning devices) (Morawska et al., 2021). These contestations neatly highlight how during the pandemic “the sociomaterialities of air, breath and the ventilation of spaces” became “central features of COVID-19 risk discourses, as have the policies, objects and practices used to manage air flow” (Lupton and Lewis, 2022: 131). This was very much the case for the project that provides the focus of our analysis, which we now introduce into the discussion.

5.3. Methods: Interrogating the project

The project in which the lead author of the paper was a participant was set up by a sustainable technologies company, in partnership with a leading behavioural change charity, an air cleaning technology developer, and NAQTS, a company that designs and develops IAQ monitors.[28] The project was established to see how well air cleaning technology works to provide safe IAQ. The focus of the project on school classrooms reflected the well-documented understanding of children’s vulnerability to poor air quality, and the significant amount of time children spend at school.

In the initial project design, IAQ monitors were deployed for the 2020 spring term in 20 classrooms across England and Wales. However, these measurements took on a different character due to COVID-19, at least in part because we inadvertently ended up measuring – and filtering – the air of empty classrooms. Subsequently an additional measurement campaign in 6 of the original 20 schools in the 2020 autumn term was planned to gather more data. These two terms can broadly be read as pre- and post-COVID-19 measures. This paper draws upon carbon dioxide (CO_2) measurements specifically, as an indicator of changing notions of good IAQ, driven by a renewed focus on ventilation due to COVID-19.

Some of the applied findings of the project feature in the account that is to follow, but we also draw upon the direct involvement of the lead author in the project, as the CEO of the company that designed and developed the monitoring technology, through examining correspondence between project partners during the process of setting up

[28] A company co-founded and run by the lead author.

and carrying out the project.[29] This included emails, project meetings and notes, progress reports, and presentations over more than a year-long period. We look back on the process of the project by deploying a combination of reflexive and relational ethnographies to both look at how “the products of research are affected by the personnel and process of doing research” (Aull Davies, 2012: 4) and also how “configurations of connections, transactions, and unfolding relations” (Desmond, 2014: 574) influenced how the doing of science was adapted to deal with the emergence of COVID-19. This relational element importantly includes a sociomaterial perspective to highlight the role of non-humans in the construction of social worlds. The account is necessarily one of a ‘partial perspective’, recognising that the knowledge produced is inherently ‘situated’ (Haraway, 1988). This includes what was measured and with what devices, who made the measurements, and where they were taken. However, by attempting to hold on to “both ends of the dichotomy” (Haraway, 1988: 180) of objectivity and relativism, by both showing the contingency of our knowledge claims and the material reality of the air that we measured, we aim to explore how the doing of science was produced and how it was destabilised and had to reform in response to a potent new actant. We also analyse government and industry statements and reports on ventilation strategies during the pandemic.

To do so we draw upon Actor-Network Theory (ANT) to think through air quality’s sociomaterial instability. ANT is an approach that envisages sociomaterial worlds as a set of ever shifting networks (Latour, 1987). ANT focuses on describing these worlds through tracing the relations between different actors in these networks (Latour, 2005). A key argument of ANT is all that entities in the world have the same potential agency to configure action, human or non-human (Sayes, 2014). In practice, ANT is less of a theory, or toolkit, and more “a highly mobile label for a stabilised conceptual repertoire concerned with generalised symmetry, networks and non-humans” (Farías et al., 2020: xxii). We position ourselves as working ‘near’ ANT (Farías et al., 2020), a term we mobilise both to recognise our close association with ANT, but also other more-than-human approaches to social inquiry (Farías et al., 2020). This does not mean to

[29] Ethical approval was obtained from the Lancaster University Faculty of Science and Technology Research Ethics Committee (FST20161) to both use the air quality data generated in this project, and the ethnographic insights from correspondence between project partners.

imply that we ‘nearly’ provide an ANT account. Rather, that we use ANT as a companion with “an adaptable, open repository. A list of terms. A set of sensitivities” (Mol, 2010: 253). We do mobilise some specific concepts from ANT that have been widely used in the social sciences, and in a sense transcend the ANT label. However, we also draw upon concepts that run alongside ANT, such as ‘matters of care’ (Puig de la Bellacasa, 2011). In using this near-ANT approach, we contribute to discourses around ‘intervention’ (Zuiderent-Jerak and Jensen, 2007), or ‘intravention’ (Estalella and Criado, 2018) in social research. This is of relevance both to increasing calls for ANT to positively intervene (López-Gómez, 2020), and for air quality science to be more ‘critical’ (Booker et al., 2023) and think carefully about its sociomaterial implications.

Unsurprisingly, our study is not the first to cast COVID-19 as a strikingly powerful actant. Indeed, Latour argues that it is an “incredible demonstration of network theory” showing “how quickly something can become global just by going from one mouth to another” (Watts, 2020). COVID-19 has been mobilised in all sorts of contexts, enacting the agency of a variety of non-humans including facemasks and toilet paper (Sikka, 2021); educational technologies and digital infrastructures to facilitate remote learning (Pischetola et al., 2021); and algorithms for contact tracing and risk assessments (Liu, 2021). We now turn to characterising the classroom assemblage as it was configured before the emergence of COVID-19.

5.4. Assembling the school classroom and its air: pre-COVID-19

A school classroom can be conceptualised as an assemblage of human and non-human actants, including pupils, teachers, assistants, cleaners, governors, textbooks, desks, computers, school timetables, school rules, curricula, among a host of other things. Given our analytical focus, we would also add windows, doors, ventilation systems, breath and breathing, the air itself, and its chemical and particulate constituent elements to this network of actants.

Our research project, with its intent to both monitor and intervene in air-relevant elements of the assemblage, added two new material actants into the school classrooms: an air quality monitor and an air cleaner. For these devices to be successfully enrolled it was pivotal that they did not disrupt the functioning classroom, and that they would slip away into the background as intermediaries free to measure and filter the air quality uninterrupted. As shown in Figure 5.1, both devices were however in plain sight in the classroom, in part because for them both to function well, they needed to be in close association with the breathed air of the classroom.

Figure 5.1: One of the school classrooms where we measured and cleaned the air.

The IAQ monitor, the NAQTS V2000 (hereafter referred to as the 'V2000') is a micro-sized air quality monitoring station (NAQTS, 2022), designed and developed by the company that the lead author runs. It was selected for this project due to its capability to measure a range of different air pollutants and environmental conditions, coming from a range of different sources. This pliability was designed in to the V2000 to both align with dominant scientific and medical research focuses on specific pollutants, but also to respond to emerging pollutants of concern, namely ultrafine particles (UFPs):

the smallest size fraction of particulate matter (PM) (AQEG, 2018). These pollutants are outlined in Figure 5.2, taken from an internal project presentation. Indeed, without the V2000, many of these elements would remain intangible as perceiving them is “inherently intertwined with the technical infrastructures that produce our relation to it” (Weber, 2021: 176). The V2000, a literal ‘black box’, acted in this capacity for the project, with its role being understood as air in, data out, with its internal workings of air quality sensors, electronics, and algorithms remaining hidden from view. The V2000’s role was to collaborate closely with the air cleaner, which continuously filtered a wide range of pollutants using different technologies from filters for particulates and gases, to disinfecting lamps.

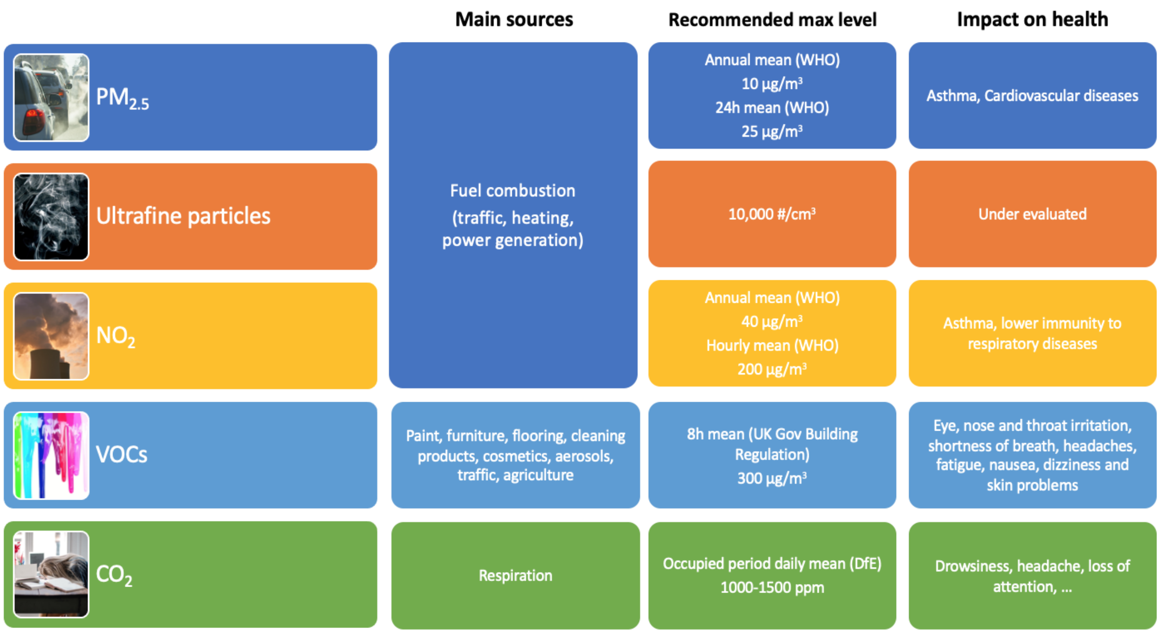

Figure 5.2: Overview of the air pollutants considered in the project, both for IAQ measurement and cleaning.

The V2000 became an obligatory passage point (OPP) for the project, as only air that would pass its sensors would be enrolled into the process of knowing the air in the classroom and would come to count. Indeed, even with the array of different measurements provided by the V2000, such is the nature of air quality science that one cannot measure the air in its entirety: some elements are destined to remain intangible, unmonitored, and unknown. None more obvious than SARS-CoV-2 itself, as it would only be after COVID 19’s emergence and combination with other material inscriptions that it would emerge as something that was being measured (albeit indirectly, a point we return to later). The V2000 also acted as the ‘spokesperson’ for

NAQTS during the day-to-day running of the project. That is, the actant that defined the interests of the group. Its role was to demonstrate its effectiveness at measuring a wide array of different air pollutants, as a business technological offering. As with the V2000, the air cleaner also acted as the spokesperson for its makers and sellers, providing a demonstration of its agency in cleaning the air, shifting from the laboratory to the real-world.

5.4.1. Carbon dioxide as a proxy for indoor air quality

As shown in Figure 5.2, CO_2 was one of the parameters measured in the project in its pre-COVID-19 form. CO_2 in indoor environments is primarily the consequence of human exhalation, and has been an integral part of understanding IAQ and building ventilation for over 150 years (ASHRAE, 2022). Despite historical disputes over whether it is an excess of CO_2 or a reduction of oxygen that causes the tangible sensations of 'stuffiness' and 'bad air' indoors, since 1872 CO_2 has been seen as a useful surrogate for bad air, rather than an air pollutant in of itself (Janssen, 1999). There is still considerable ongoing research evaluating the effects of CO_2 on a range of different health outcomes, including worsened cognitive functions, and sick building syndrome symptoms. Nonetheless, it is still not possible to judge whether CO_2 itself is responsible (Lowther et al., 2021).

This surrogacy, or proxy status, has underpinned the development of modern standards for managing ventilation. Indeed, CO_2 has its own centres of calculation where knowledge production is stabilised, so that the construction and dissemination of knowledge can move more easily to other places. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), and the European Committee for Standardization (CEN), underpin most modern North American and European ventilation requirements. In 1989 ASHRAE designated a limit of 1000 parts per million (ppm) of CO_2 as an indicator of an appropriate air ventilation rate per person (ASHRAE, 2022). However, despite this figure not being based on IAQ per se, but on the perception of human body odour by building occupants, it has commonly been misunderstood as an indicator of acceptable IAQ (ASHRAE, 2022), and has continued to permeate ventilation practice in a range of different settings.

The governance of the air in school classrooms is a fractured affair. There are a variety of different standards and protocols to organize the school's air and air infrastructure, from standard building codes, to health and safety regulations, to specific requirements for special rooms such as science labs. Building Bulletin 101 (BB101) is the main reference document for ventilation, thermal comfort and IAQ in school buildings in the UK and was initially released in 2006 and last updated in 2018. As of the 2018 update, it provides performance standards for CO_2, with the following key recommendations on concentrations (ESFA, 2018):

- For mechanically ventilated buildings, a daily average concentration of CO_2 of less than 1000 ppm, during the occupied period. The maximum concentration should also not exceed 1500 ppm for more than 20 consecutive minutes each day.
- For naturally ventilated buildings, a daily average concentration of CO_2 of less than 1500 ppm, during the occupied period. The maximum concentration should also not exceed 2000 ppm for more than 20 consecutive minutes each day.

Despite these standards, neither BB101 as guidance, nor the CO_2 sensors that were installed in some school classrooms had enrolled sufficient support to in practice control the CO_2 content of the air in school classrooms. Indeed, research carried out in school classrooms prior to COVID-19 demonstrated that many classrooms regularly exceeded the limits outlined in BB101 (Chatzidiakou et al., 2012; Mumovic et al., 2009). Similar trends can be seen in the first phase of 'pre-COVID-19' measured data the V2000 produced in our project (see Figure 5.3), with the daily mean CO_2 concentrations varying from school to school, and some not complying with the BB101 thresholds.

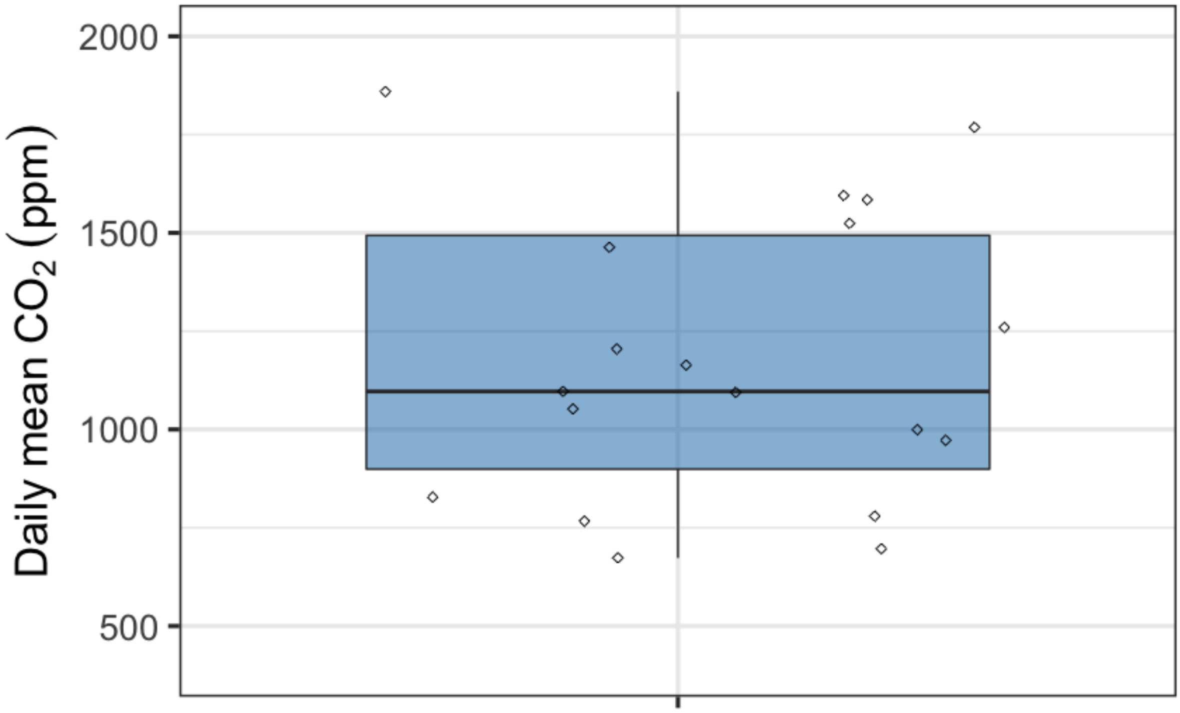

Figure 5.3: Box plot of the daily mean CO_2 concentrations across the 20 schools before the first COVID lockdown. Each point is a school. The lower and upper box boundaries represent the 25th and 75th percentiles respectively. The line inside the box is the median value.

This shows that BB101, prior to COVID-19, was not a particularly forceful actant in the school classroom assemblage. This changed however, and we will show how the creation of a 'structured envelope' – that is, the social, technical, and political context that permits or prevents the mobility and durability of certain actants – around BB101 (Law, 1984), including the installation of CO_2 sensors, became an ongoing process of stabilising BB101 as a more forceful actant.

5.5. Assembling the school classroom and its air: with COVID-19

The airborne spread of COVID-19 through viral particles quite radically shifted the focus of IAQ in the project from non-human to human actants as responsible for enrolling harmful air contaminants into the assemblage of the school classroom. This change in focus – in part due to the urgent nature of the crisis – led to a critical role for ventilation in bringing in outdoor air to dilute the concentration of the virus (Morawska and Cao, 2020). Often referred to as 'fresh air', a notion steeped in the focus on the health effects of exposure to certain pollutants, the promotion of ventilation reinforces the long-standing idea that bringing in outdoor air improves the quality of the air that we breathe indoors, a point we will return to later. In this section we outline how the entry of COVID-19 destabilised the applied research project, now re-directed towards the demands and priorities of the pandemic.

5.5.1. Measuring ‘fresh’ air

To measure how much outdoor air is being brought indoors, we were able to turn to the V2000 as an already present part of the classroom assemblage. Its capacity to generate a wide range of measurements meant that we could readily adapt to the new most important elements of concern, namely CO_2. Directly measuring concentrations of ultrafine particles (UFPs) may have seemed the obvious choice given that the aim of managing pandemic breathing is to dilute the number of indoor airborne viral particles. Indeed, this was something that NAQTS preferred, given its measurement of UFPs is its most novel business technological offering. However, as Latour (2000: 116) remarks, the objects of science, in our case UFPs “will have no scruples whatsoever in […] behaving in the most undisciplined ways, blocking the experiments, disappearing from view, dying, refusing to replicate, or exploding the laboratory to pieces.” For us, the fact that UFPs (as measured) are so unstable made them hard to discipline: they can be found in very high or low concentrations, they react with other elements of the air including sticking to themselves, and they come from many sources indoors and outdoors. Moreover, to measure UFPs the V2000 simply counts the number of particles in a cubic centimetre with no specific information on what a particle is made of. With thousands of particles typically in a cubic centimetre of indoor air, attributing any one of those to COVID-19 is akin to trying to find a needle in a haystack. All-in-all this makes it difficult to say with any certainty whether high or low concentrations of UFPs necessarily relate to risks of airborne virus transmission. Here the intangibility of SARS-CoV-2 becomes clear, as while it was directly measured, this was not enough for it become known as it is indistinguishable from any other measured particle.

We found a much more willing and enrollable ally in CO_2. Whilst this shift in focus to CO_2 could have destabilised the project by, for example, being at odds with the interest of NAQTS as it side-lined the most novel aspect of its technology offering, this did not happen. As noted earlier, CO_2 in indoor environments primarily comes from human exhalation, so it is a useful proxy for exhaled airborne viral particles (Rudnick and Milton, 2003). It is also very stable, both in the sense that it is an inert gas immune from chemical reactions in normal environmental conditions, and that its outdoor concentrations do not vary greatly. That all means that by measuring changing rates of CO_2 indoors, you can see the rate at which outdoor air is coming in and diluting indoor air. In other words, it can be used as an indicator of ventilation.

The process of measuring the rate by which outdoor air replaces indoor air is typically expressed as the air change rate (AC/H), the measure of the air volume added to or removed from a space in one hour. This is calculated using the CO_2 concentration decay method, which has an experimental logic: 1) CO_2 is injected into a space, 2) the injection is then stopped and the CO_2 is given time to mix so it is more uniform across the space, and 3) the decrease of CO_2 begins and is recorded over a given amount of time, or until the CO_2 concentration reaches a certain threshold (Cui et al., 2015). In our real-world setting, the injection of CO_2 is provided by the occupants of the school classroom through exhalation. Looking at the variation of CO_2 taken from one of the schools over a week, five distinct peaks can clearly be seen (Figure 5.4).

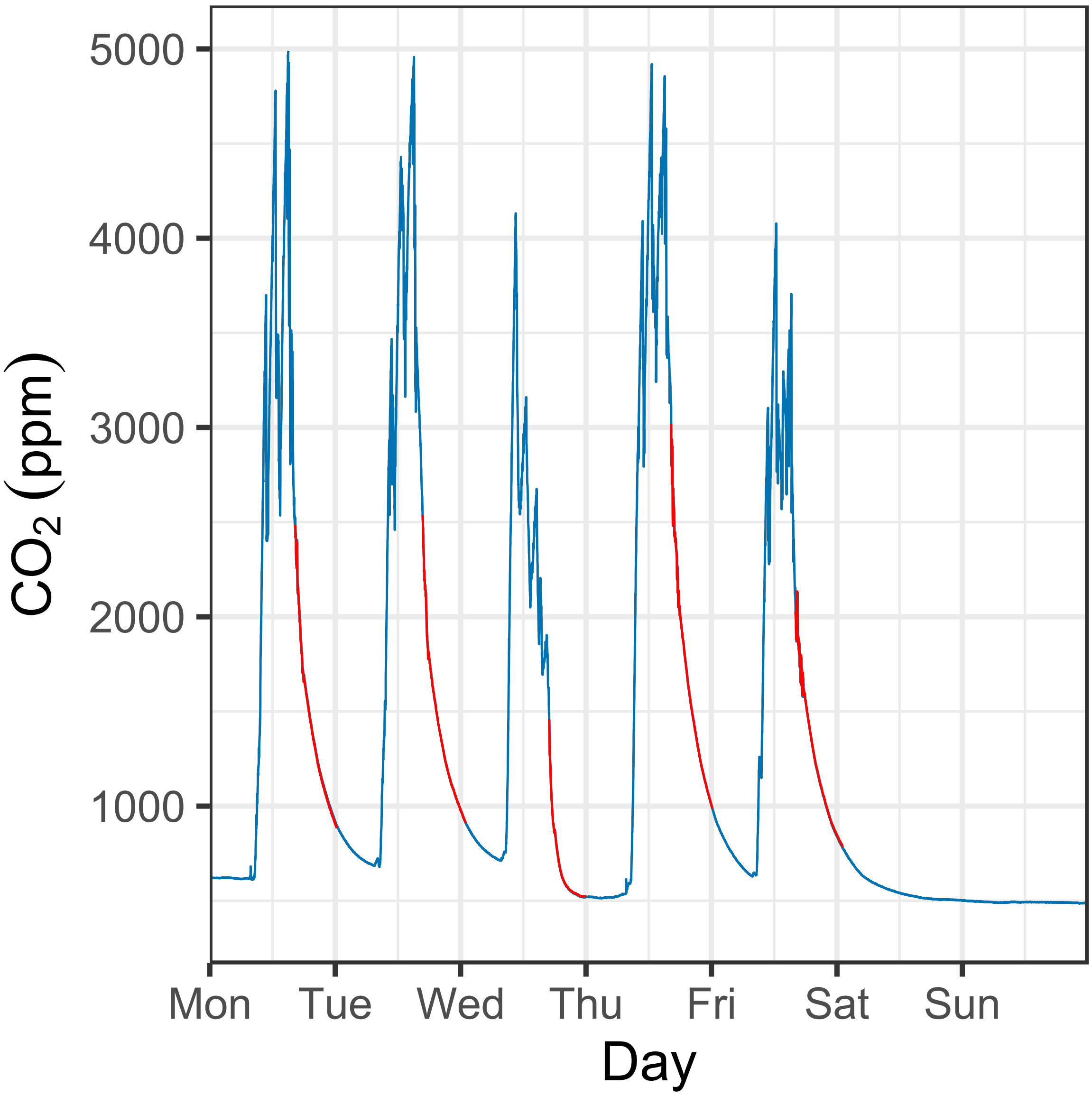

Figure 5.4: Trends for CO_2 across the week in a single school classroom showing periods of occupancy and non-occupancy. The air change rate is calculated from the decay (in red) at the end of the school day.

The peaks and troughs in Figure 5.4 are associated with school timetabling, including children leaving the classroom for their breaks. The end of the school day is indicated by the red sections of the line, showing the exponential decay in CO_2 concentrations that occurs when no people are present in the classroom. It is from this period that we were able to calculate the AC/H to understand the rate by which outdoor air is coming in and diluting indoor air. In this way, the translation of a host of different human and non-human actants into a single measure, or material inscription, created an ordered representation of networked interactions, allowing us to provide a quantified judgement of how well a building's ventilation system was performing. This allowed scientific knowledge to effectively circulate both within our project, but also other larger networks concerned with classroom IAQ.

5.6. Evidencing potential harm

On their own, the inscriptions generated of CO_2 concentrations in the classroom and ventilation rates did not constitute a powerful mediator that would “transform, translate, distort, and modify the meaning or the elements they are supposed to carry” (Latour, 2005: 39). As explained earlier, measuring CO_2 as an indicator of IAQ has a long history, but with relatively little obvious practical consequence. However, it was the enrolment of a host of other actants, including scientific calculations, and COVID-19 scientific advisory bodies and task forces, that allowed COVID-19 to reassemble the sociomaterial functioning of our project.

The use of the Wells-Riley equation (Riley et al., 1978; Wells, 1955) – a simple and quick assessment of the infection risk of airborne transmissible diseases – was a particularly powerful inscription device during COVID-19. The Wells-Riley equation contains several variables, including ventilation rates, the infectivity of a virus, and the breathing rate of a susceptible individual. Figure 5.5, applying the formula-based logic of the equation, highlights the importance of ventilation in managing COVID-19 – and other disease – risks, with small improvements in the volumetric flow rate (another measure of ventilation) having significant reductions to the probability of infection. Accordingly, each of the 20 schools’ data for the pre-COVID-19 spring measurement campaign were analysed. When performing the calculation other infectious diseases were used for comparative purposes, to highlight – and make ‘real’ – the airborne ineffectiveness of COVID-19. The different coloured lines on Figure 5.5 represent different types of infectious diseases, and the dots on each line represent a different school. An increase in Q, the volumetric flow rate in metres cubed per hour (m^3 / h), decreases the risk of infection for various diseases. Figure 5.5 shows that there was the potential for huge reductions in the probability of infection with modest improvements to ventilation. For example, for COVID-19, a Q of 50 m^3 / h would see an around 80% probability of a pupil being infected during one school day in the presence of one infected person in the classroom. Whereas a *Q* of 100 m^3 / h would see this probability drop to around 40%.

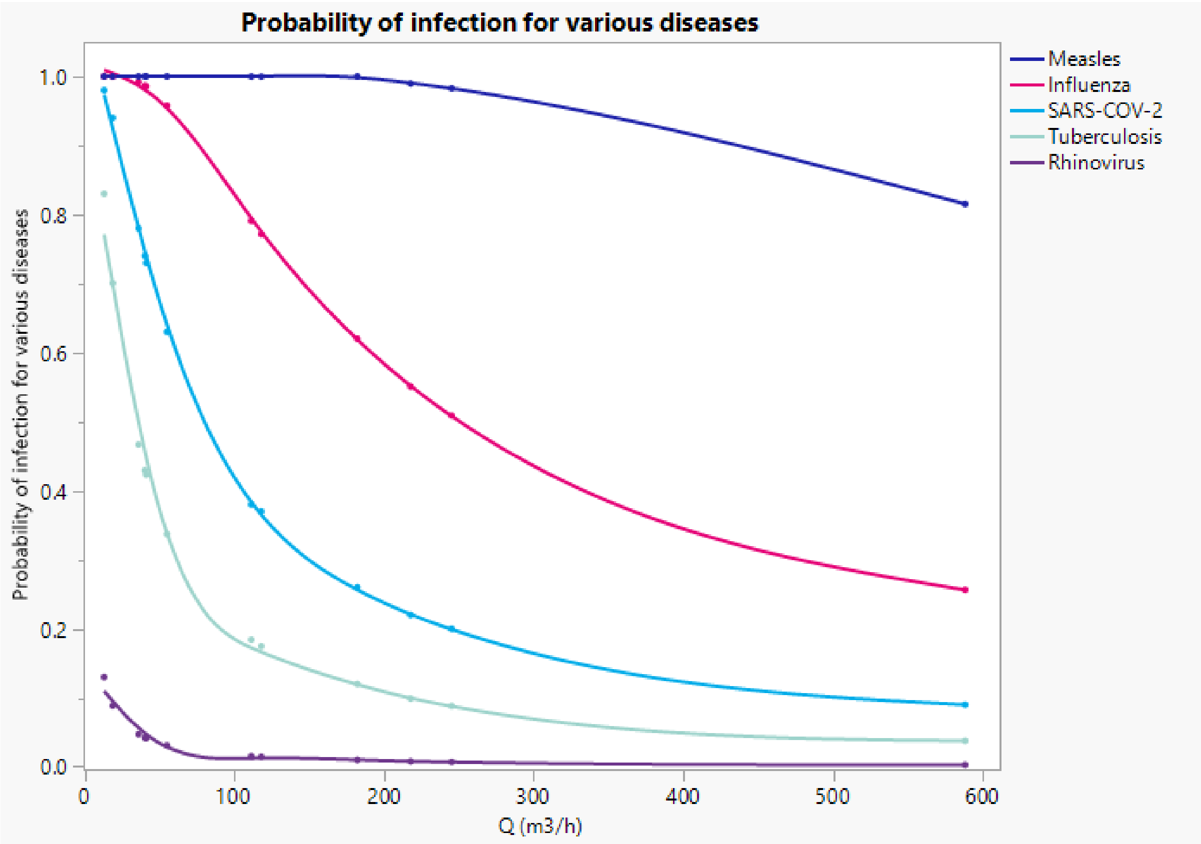

Figure 5.5: The infection risk of various airborne transmissible diseases calculated using the Wells-Riley equation.

It was the use of the Wells-Riley equation that allowed for a figure to be put on the likelihood of contracting COVID-19 based on the measured classroom CO_2 concentrations (Rudnick and Milton, 2003). This helped to form a structured envelope around CO_2 inscriptions, that would permit them to become what Latour refers to as an ‘immutable mobile’ (Latour, 1987), that is, an object that is stabilised by actor-networks and permit the reproduction of actions across different contexts and places. What constitutes breathable air in classrooms was stabilised around this immutable mobile, allowing us to feedback information to the schools on how to improve their IAQ (something that we expand on in the next section). That is not to say that the contents of this immutable mobile, or black box, went undisputed. For the Wells-Riley model, the ‘quantum’ which represents the ‘infectivity’ of a virus was a point of contention within the project. The value of this quantum, *q*, is of great significance to the Wells-Riley model, with a greater *q* value increasing the likelihood of infection. Indeed, deciding what *q* to use for our project was a challenging point. An initial choice was made and explained as follows:

> "I have picked the quantum […] related to individuals doing light exercise while talking. This will be a worst case scenario where all kids move around the classroom all day, at full capacity and without any face protection." (Email between project participants, 3rd July 2020).

However, this quantum was later changed, in part considering that using the absolute 'worst case scenario' could lead to unwarranted worry and concern. This highlights the challenges of providing scientific advice when "facts are uncertain, values in dispute, stakes high and decisions urgent' (Funtowicz and Ravetz, 1993: 744).

These inscriptions that we generated destabilised the way the science for the second part of the project was done, and the goals of the research project actors. Indeed, all of a sudden, the V2000 would become not just an intermediary but a powerful mediator in the network. It was no longer transporting traces without meaning, as the CO_2 inscriptions it produced were strengthened by their combination with other scientific equations, forming an immutable mobile, by the humans who spoke on behalf of the network. This immutable mobile would alter the relationship between people at the school and their ventilation systems (whether that be natural or mechanical). We evidence this reassembling in the next section of the paper.

5.7. Matters of air-care

Despite early contestations around the 'airborne' nature of SARS-CoV-2 (Morawska and Cao, 2020), building engineering advice was early to recommend "that indoor spaces should be ventilated as much as reasonably possible" (CIBSE, 2021: ii) to manage the spread of COVID-19. These industry recommendations were endorsed in written advice by the UK government's Scientific Advisory Group for Emergencies-Environment and Modelling Group (SAGE-EMG), stating that "ventilation should be integral to the COVID-19 risk mitigation strategy for all multi-occupant public buildings and workplaces" (SAGE-EMG, 2020: 3). These actions were seen as even more important during winter where it was stated that ventilation should be "the primary mitigating measure" (Burridge et al., 2021: 15), as buildings tend to be less well ventilated in winter in order to maintain thermal comfort indoors.

In this context, within the project it was no longer ethically viable for us to remain in the background as intermediaries free to measure and filter the air quality uninterrupted, because the contours of the social fabric surrounding the school classroom and its air had now been made materially visible. Instead, we had to take on a more active role to reconfigure the assemblage during the autumn term through the various inscriptions that were generated. Indeed, the focus of our inscriptions became to *improve* ventilation to minimise airborne virus transmission, rather than to just characterise the effectiveness of the air cleaner. In a sense these are “competing air regimes” (Brown et al., 2020), as increasing ventilation rates can reduce the effectiveness of an air cleaner, as it is much easier to remove an air pollutant from a sealed room, than it is to have the room open to more outdoor air permanently coming in. As Dr Gary Fuller, a prominent air quality measurement scientist aptly puts it, filtering outdoor air is “like trying to take the milk out of your tea” (Fuller, 2018).

Between the two phases of the campaign, the behavioural change charity fed back to the schools on the data collected from the spring campaign through a series of bespoke reports. These reports highlighted the importance of increasing ventilation rates to reduce the infection risk of COVID-19, as well as signposting to other resources to develop clean air action plans to tackle air pollution in and around the school. Ventilation was enacted as a material practice to create breathable classrooms: AC/H increased, and the daily mean CO_2 concentrations in classrooms substantially decreased. Figure 5.6 illustrates this, with the boxplots on the bottom showing the increase in ventilation rates between the two campaigns, and the boxplots on the top showing the reducing daily mean CO_2 concentrations.

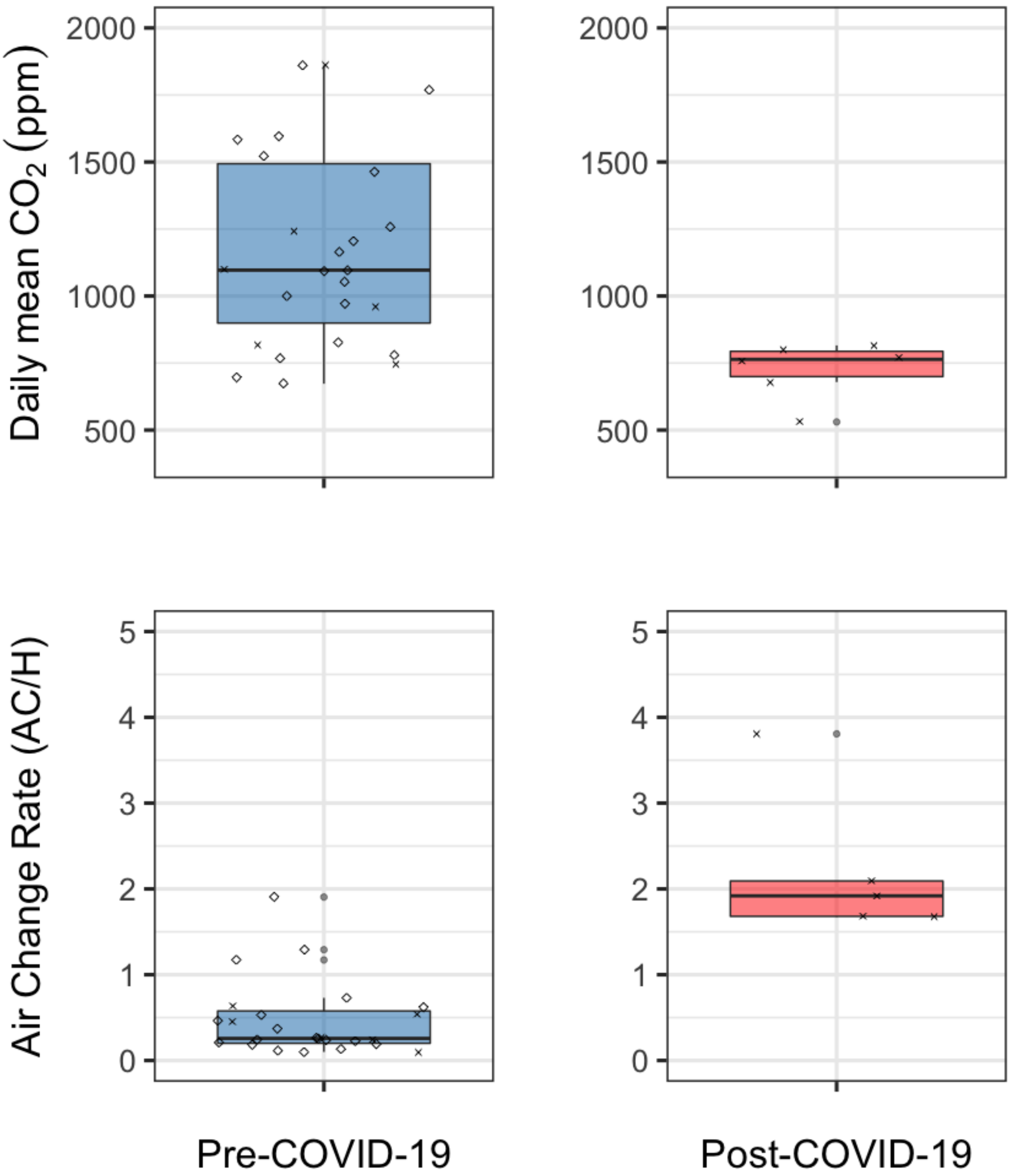

Figure 5.6: Daily mean CO_2 and AC/H pre- and post-COVID-19 measures. The lower and upper box boundaries represent the 25th and 75th percentiles respectively. The line inside the box is the median value Each point is a school. Pre-COVID-19 figures display data from all the 20 schools. Data points marked with a cross represent schools that were involved in both the pre- and post-COVID-19 measures monitoring campaigns.

These representations enabled the connection of humans to the air in school classrooms to be revealed, and enabled judgements to be made about attempts to reconfigure classroom air to make this connection less prominent. The changed understanding of good IAQ led to CO_2 becoming the dominant measure of IAQ and this, alongside the calculations provided by the Wells-Riley equation, formed the immutable mobile that stabilised our network of science in action and permitted the reproduction of actions across different contexts, ultimately leading to altered material practices around ventilation across the schools in our project. While the extent to which these increases in ventilation were the result of our interventions – rather than wider public messaging – are unknown, they nonetheless highlight a willingness to intervene in the continual unfolding of the classroom assemblage.

The inscriptions which were presented as ‘matters of fact’, denoted where the air was good or bad, breathable or non-breathable. However, Latour’s (2004) concept of a ‘matter of concern’ presents the oft-touted ‘matters of fact’ as being part – and a result – of a wider set of entangled social and political interests. It is easy to see how the enrollment of IAQ monitors and air cleaners, and the business and research interests that they represented can place the matter of facts that we generated into a wider socio-political regime of knowing, and organizing the governance of the air indoors (Whitehead, 2009). However, we argue that the entry of COVID-19 into the school classroom, and the subsequent human willingness to intervene in the continual unfolding of the classroom assemblage, shifted the air from a matter of concern, to a ‘matter of care’ (Puig de la Bellacasa, 2011). Puig de La Bellacasa (2017: 64) argues that “transforming things into matters of care is a way of relating to them, of inevitably becoming affected by them, and of modifying their potential to affect others” (Puig de La Bellacasa, 2017: 64). This distinction extends the care analogy of a matter of concern to advocate for both the material practice of taking practical responsibility and *doing* care, but also as an ethico-political obligation concerned with how “ways of studying and representing things can have world-making effects” (Puig de la Bellacasa, 2011: 86).

Practicing “air care” (Brown et al., 2020) for matters related to air pollution might mean caring for “those who can be harmed by an assemblage but whose voices are less valued […] – for example […] babies in prams whose noses stroll at the level of SUV’s exhaust pipes…” (Puig de la Bellacasa, 2011: 92). For matters more directly related to the airborne spread of disease (including COVID-19), it might also mean coughing in the right place at the right time to resolve and displace “pollution anxieties to the immediate atmosphere of the body, to other surfaces, objects, clothing, fabric, hands, materials and handkerchiefs" (Brown et al., 2021: 275). Maybe we were already doing care for the air and its particularly vulnerable breathers by making it visible through monitoring IAQ and filtering it with air cleaners. However, the COVID-19 induced reconfiguring of the role of science in this project produced a stronger ethic of care, becoming less about gathering evidence, and instead focused on intervention and improvement (Levy, 2021).

The principle of action over description following the arrival of COVID-19 raises the question of what IAQ science might look like if general air quality was treated with an iota of the same urgency. Indeed, these tensions form part of a wider discussion on the appropriate role of science when we know that the air is harming people already (Booker et al., 2023). As well as what role ANT accounts can have in a world where producing 'neutral' accounts is less palatable, and instead ANT should aim to positively intervene in the making of our sociomaterial worlds (López-Gómez, 2020).

5.8. Still unstable air

In this paper we have shown how the arrival of COVID-19 in school classrooms changed how the air and its qualities became made, known, and organized within our applied research project. However, these orderings remain more generally unstable. Different interpretations of research evidence on transmission pathways for COVID-19, that is whether they are transmitted by droplets or aerosols (Jimenez et al., 2022), has led to the prioritisation of a host of different classrooms interventions. Our project tended towards the aerosol transmission interventions of ventilation and demonstration through CO_2 measurement. However, this raises the question of to what extent our project showcases a process of reassembling that is in some form being reproduced on a wider scale. Moreover, whether this reassembling is here to stay, and how it might relate to questions of inequalities.

Methods of managing COVID-19 are more generally stabilising around aerosol transmission and hundreds of thousands of CO_2 sensors have been deployed in schools around the UK, with specific advice from the UK Department for Education (DfE) about where to place the sensors, how to interpret their readings, and what actions to take if concentrations are above certain thresholds (DfE, 2022b). Surveys undertaken by the DfE in June 2022 suggest that:

> "96% of settings that responded to the survey confirmed they had begun using the CO_2 monitors provided… Of those settings that had begun using the monitors: 95% confirmed they were able to use them to identify when ventilation in a room needed to increase" (DfE, 2022a).

However, the pandemic infrastructures that have been enacted are consequences of a particular moment in time, and there is no guarantee that they will stay. For CO_2 sensors, this consolidation is threatened by different organizations attempting to become centres of calculation with disputes over what is an 'acceptable' CO_2 concentration. For example, the National Education Union (NEU) have suggested different thresholds of acceptable IAQ based on CO_2 of 800 ppm (NEU, 2022), after following advice from SAGE EMG (2020), and CIBSE (2020). The UK government, on the other hand, sticks by its previous recommendations in BB101 and uses 1500ppm (UK Parliament, 2022). These disagreements highlight that despite their name, immutable mobiles are not always interpreted and acted upon in similar ways. For example, teachers remain an obligatory passage point for schools, in practice implementing natural ventilation, deciding when or not to open windows and doors. Even in mechanically ventilated classrooms, where the reach of metrological regimes of measurement and organized governance (Barry, 2002; Calvillo, 2018) place CO_2 data in a 'structured envelope' (Law, 1984), there may well still be a human in the loop. This is often a school caretaker, who is dictating how much classrooms breathe based on criteria that may well extend beyond the airborne transmission of viruses, such as thermal comfort and energy efficiency. This highlights that "government and science operate in contingent places (as opposed to an abstract, frictionless space of absolute science and government)" (Whitehead, 2009: 213). This contingency denotes that the form the assemblage takes will vary from location to location, and how humans will interpret and use these immutable mobiles is far from stable. Particularly in a context where teachers have many competing demands, including the energy crisis that currently looms over the UK.

It is within this variation that we might ask questions about inequalities. IAQ scientists were undoubtedly delighted to see the widespread monitoring of IAQ in UK schools, providing a large dataset for a previously 'undone science'. However, they have cautioned for a long time that IAQ is far more than just CO_2. IAQ is a much more complicated mixture of primary pollutants originating from social practices and material technologies both indoors and outdoors, and secondary pollutants emerging from chemical reactions in the air (e.g. Habre et al., 2022). This is important to recognise, as how IAQ is defined influences relations between actants. Indeed, the school classroom is not a hermetically sealed box, detached from its physical or social location. In fact, reassembling classroom air to manage pandemic breathing has made classroom IAQ *more* connected to its location, through the direct consequence of bringing in more outdoor air, fresh or otherwise. This is important for questions of inequalities because the assumption that outdoor air is 'fresh' is problematic, as in many urban locations in particular, we may be replacing one problem with another: in this case, viral particles with polluted outdoor air.

Furthermore, the socio-technical re-ordering and deployment of hundreds of thousands of CO_2 sensors is reinforcing IAQ as a matter of 'personal care' (Whitehead, 2009). While the UK government does signify IAQ a matter of concern through the proliferation of CO_2 sensors, it does not hold itself accountable for the actual mitigation of harmful levels of pollution in the first place. Instead, the UK government's response was to enrol CO_2 sensors to enact ventilation through behaviour change, and to make it explicitly clear that "remedial work to improve ventilation remain the responsibility of individual settings" (Balogun and Wiebe, 2022: 34). However, solely focusing on changing behaviours to reduce exposures fails to account for individual actions being limited by social-technical structures (Booker et al., 2023), such as the quality of the air outdoors. Indeed, defining CO_2 as IAQ, and placing the onus on the individual to change their behaviours to reduce their exposures, is perpetuating "the notion that indoor spaces may be physically and socially isolated from the world at large" (Biehler and Simon, 2010: 175). IAQ becomes the responsibility of those inside the building, even though outdoor air pollution does not bounce off the front door. Indeed, concentrations of outdoor air that are so poor that they are deemed illegal can flow into the indoor environment and suddenly become the problem of the inhabitants.

The enrolling of CO_2 sensors has been a positive step in terms of making the invisible visible indoors, and we should be wary to let perfect be the enemy of good. However, just as Latour's door stopper conditions us on the socially acceptable use of a door

(Johnson, 1988), so do CO_2 sensors condition us on how to relate to the air indoors. They define what is breathable and non-breathable air indoors, and influence the unfolding relations between humans and non-humans in managing and controlling the relationship between the air indoors and outdoors. The long-term implications of this still are still being played out.

5.9. Conclusion

As Sloterdijk (2009: 19) has noted, a “theory of unbreathable spaces is still obscure”, despite the development of tools and technologies over hundreds of years aimed to protect breathers from their surrounding environment (Kenner, 2021). Where contributions have been made, they mainly relate to the air outdoors while “indoor environments remain considerably less theorized” (Biehler and Simon, 2010: 175). We contributed to discussions on unbreathable spaces in indoors environments by showing how the air became destabilized due to the arrival of COVID-19 in school classrooms. In doing so, the air’s qualities became made and known differently, transforming the air from “the medium of everyday life to an object of concern and daily intervention” (Nguyen, 2020: 457). In this paper we have shown how a research-business project became re-assembled to COVID-19. The redefinition of air pollution to account for COVID-19 led to a focus on removing viral particles emanating from humans indoors through bringing in outdoor air. Despite the considerable scientific and political apparatus that utilised CO_2 as an indicator of good IAQ through bringing in outdoor air (pre-existing COVID-19’s emergence), it had not been a particularly forceful actant in school classrooms. However, measurements of CO_2 were ultimately strengthened by their alliance with Wells-Riley inscriptions, forming an immutable mobile, that would alter the relationship between people at the school and their ventilation systems. These were powerful actants structuring the school classroom assemblage to decrease the connection of humans to the air in school classrooms through increasing ventilation rates. However, the air remains unstable, and whether these actants will continue to be a significantly agentive is unresolved, with different organizations attempting to become centres of calculation, and teachers remaining an obligatory passage point in many schools.

COVID-19’s central role in organizing IAQ is likely to eventually fade, and as it does “social scientists must carefully identify and challenge the normalization and institutionalization of these pandemic infrastructures, connections, and norms that have the potential to reshape post pandemic institutions, social orders, and everyday life" (Liu, 2021: 22). Moreover, as other everyday digital infrastructures have been shown to have inequality generating mechanisms (Liu 2021), this raises the question of who gets to benefit and who is harmed through configuring the school classroom in this way. This both relates to the effects of ordering the air through CO_2 inscriptions, potentially replacing one problem with another: in this case, viral particles with dirty outdoor air, as well as making IAQ an issue of 'personal care'.

It is in this space that we might to consider how to better care for indoor air in the future. In particular how we might do a more 'critical' air quality science (Booker et al., 2023), that practices care by thinking further than measuring the damage caused by air pollution with increased precision. This means a more interventionist approach focused not only on reduced exposures and emissions, but also appraising carefully what world(s) air quality science is both making visible, but also promoting for the future.

6. A Critical Air Quality Science Perspective on Citizen Science in Action (Paper 3)

Booker, D., Walker, G., Young, P.J., & Porroche-Escudero, A. (2023). A Critical Air Quality Science Perspective on Citizen Science in Action. *Local Environment*, *28*(1), 31–46. https://doi.org/10.1080/13549839.2022.2118700

Abstract

Air pollution is a hybrid phenomenon, understood and produced through social practices and material environmental processes. This hybridity leads us to engage critically with how air quality science is carried out. In dialogue with the Critical Physical Geography subdiscipline, we propose a Critical Air Quality Science (CAQS) framework to study air pollution's sociomateriality. We use CAQS to illuminate four tensions in the dynamics of knowledge production during a citizen science air quality monitoring project: making undone science matter, blurring "insiderness" / "outsiderness", traffic as both life and death, and changing behaviours versus changing systems. Drawing on interviews with citizen scientists, we outline the implications of these tensions for air quality research design and reporting. The CAQS framework provokes critical thought about the consequences of how air quality science understands, creates, and communicates knowledge, and how we can reconfigure our relations with the air to minimise air inequalities.

6.1. Introduction

Established knowledge on air pollution's material properties and effects has been vital in the development of guidelines and regulations aimed at improving air quality (e.g.

WHO, 2021). While this knowledge is important, it has not resolved the question of what poor air quality is, how it manifests, or how it can be known. This is because air pollution's materiality is not self-evident: it is a 'hybrid' entity, produced through social practices and material environmental processes, known in ways that are socially defined by different actors, and not only revealed through applying standard scientific methods and assessments (Cupples, 2009).

Embracing air pollution as a hybrid phenomenon requires us to rethink how we come to understand it and to reflect on the epistemic boundaries that are established in air pollution knowledge production. Challenges to the relevance of dominant forms of air pollution knowledge, and mobilisation of claims of epistemic injustice (Fricker, 2007), have come from community groups suffering from air pollution. Whether exposed to short-term 'spikes' of air pollution that are averaged out by regulators (Ottinger and Sarantschin, 2017), or having higher rates of asthma in the neighbourhood that have not yet been linked to air pollution (Brown et al., 2003), community groups have questioned the data of governmental or industrial monitoring regimes (e.g. Ottinger, 2010; Gabrys, Pritchard, and Barratt, 2016). They sought to remedy 'undone science' – a concept that has been mobilised to refer to areas of research that are left unfunded, incomplete, or ignored (Frickel et al., 2010) – by generating their own data. In so doing community groups often collaborate with experts to access their knowledge and skills, including the use of air quality monitoring equipment, contributions to data interpretation, and allyship in campaigning for change (e.g. Ottinger, 2010; Gabrys, Pritchard, and Barratt, 2016). However, research has shown that citizens can understand and use air quality data differently to traditional air quality experts (Bickerstaff, 2004; Gabrys, Pritchard, and Barratt, 2016; Ottinger, 2010). This creates tensions around the appropriate form of expertise that 'sympathetic' scientists should provide and the processes through which their collaborations with citizens and communities should be enacted.

It is at this nexus that we explore an air quality research that acknowledges air pollution's material significance and also embraces its hybridity and multiplicity (Cupples, 2009; Garnett, 2017), culminating in an approach that we call critical air quality science (CAQS). We combine this theoretical argument with a constructivist approach to understand how people make sense of the air and ascribe it meaning

(Bickerstaff and Walker, 2003), drawing on both semi-structured interviews with members of the community group ‘Better Old Swan’ based in Liverpool, UK, and our own reflections – as academics and technical experts – involved in this group’s citizen science project on air pollution. We ruminate on CAQS in practice, interrogating the contestations, contradictions, and dilemmas that arose during this project, by opening up four tensions: 1) the challenges involved in making citizen-generated air quality data matter in policy and practice, especially as the project went beyond the dominant paradigm of regulatory air quality monitoring practice; 2) the construction and contestation of ‘insider-outsider’ designations and their implications for the design and reporting of air quality research; 3) the potential unintended sociomaterial impacts of air quality research, including the dilemmas raised when communicating its results; and 4) the dilemma as to whether to focus on short term goals to reduce air pollution exposure through behavioural changes, or longer-term goals that address the structural causes of air pollution. We discuss the implications of these tensions for the practice of CAQS and reflect on how to address them when undertaking future CAQS work. Before focusing on the case study analysis, we begin by laying out the body of previous work that has provided inspiration for the notion of CAQS.

6.2. Constructing a Critical Air Quality Science

Approaches to integrating the social and natural sciences have a long history. While this has included air quality science specifically (e.g. Cupples, 2009), much air quality research remains in disciplinary silos based on problematic dichotomies between nature and society, despite it “not [being] immediately clear whether air pollution belongs to nature or to culture” (Cupples, 2009: 211). Humans have always manipulated the air around them, such as by fire or exhaled viral particles. Moreover, the way that we describe the air is entangled in our own values (Cronon, 1996). For example, air quality science is “motivated in large part by a desire to purify what is seen as becoming contaminated, to prevent the mixing of the atmosphere, pollutants and bodies” (Cupples, 2009: 211). However, it is seeking nature’s ‘fresh’ air that can ‘get us back to the wrong nature’ (Cronon, 1996). That is, one without humans in it. It is in this space that we propose CAQS, which acknowledges air pollution’s material significance by doing physical air quality science, while recognising the importance of social dynamics in constructing what we do – and do not – know, and who that knowledge serves.

The recently developed Critical Physical Geography (CPG) subdiscipline provides a useful framework to study “material landscapes, social dynamics, and knowledge politics together, as they co-constitute each other” (Lave et al., 2018: 6). While CPG encompasses a diverse range of fields, methods, and epistemologies, it is centred on three main intellectual tenets: hybridity, reflexivity, and power and justice (Lave et al., 2018). While we use CPG’s tenets as a source of inspiration for constructing CAQS, our aim is not simply to transpose CPG to the field of air quality science, but rather to be in dialogue with it. We in part make this distinction because air quality research has strong foundations in disciplines beyond geography, especially in chemistry and physics. In the following sub-sections, we take the tenets of hybridity, reflexivity, and power and justice in turn, explain their meaning, and value to a focus on air pollution.

6.2.1. Hybridity

The tenet of hybridity recognises that the material world is tangled in political, social, and economic relations and is thus co-produced by social practices and environmental processes (Whatmore, 2002). Therefore one cannot rely solely on social or physical explanations for the environment (Lave et al., 2014). In the case of air pollution, it is as much the result of the intertwining of patterns of transport, consumption, and city planning as it is of atmospheric chemistry, meteorology, and climate change. It follows that assigning an appropriate weight to social and material explanations of patterns of air pollution becomes complicated and separating them a potentially futile activity. For example, Clifford (2020) explains how dust is often identified as a natural source of air pollution, compared to human made sources in urban areas such as vehicle emissions. However, this is based on a false dichotomy between nature and society: dust storms are significantly exacerbated through land-use practices that degrade soils. Therefore, approaches to understand – and ultimately improve – air quality should be ‘hybrid’ and embrace air quality’s social and material aspects, i.e., its sociomateriality (Cupples, 2009).

6.2.2. Reflexivity

Social, political, and economic relations affect the scientific gaze: the questions asked, the way research is conducted, and even research findings (King and Tadaki, 2018). For air quality science this gaze amounts to a 'metrological regime' (Barry, 2002), whereby standardised ways of knowing the air dictate what comes to count as air pollution, and what concentrations are harmful. This requires researchers to be reflexive, to probe why certain scientific concepts and theoretical frameworks are being used, what worlds they are making visible, what relationships they are legitimising (Tadaki et al., 2015), and why we might favour some knowledges over others (Cupples, 2009). The concept of reflexivity has a long history within the social sciences. Through looking at science in action to tell a warts-and-all story of how scientific facts are *constructed* (e.g. Latour, 1987), it is touted as a way to express the situated – or partial – nature of scientific knowledge (e.g. Haraway, 1988). Embracing reflexivity is not to say that standard scientific methods are wrong, but that they are partial and can exclude alternative ways of understanding. For example, scientific air quality risk assessments rely on assumptions about air pollution exposure risks based on 'average' people that are far from representative, reduce health effects to population-level probabilistic measures, and embed an approach that air pollution can be known and controlled to 'acceptable' concentrations, rather than favouring a precautionary approach (Ottinger, 2017a).

6.2.3. Power and Justice

Scientific knowledge production is inherently political as scientists are deeply enmeshed in a range of social relations (King and Tadaki, 2018). Therefore, it has sociomaterial impacts (Law, 2018). The tenet of power and justice focuses on these impacts and can be understood as an extension of reflexivity. For CAQS the choice is not between being a political activist or an apolitical detached observer, but between a range of potential political positions as "through our practices of research and our production of knowledge, we become agents of change […] our research is published and/or incorporated into environmental policy and practice" and it aligns with "particular applications and/or agendas and therefore particular politics" (Law, 2018: 89–90). Air quality scientists therefore need to consider carefully the implications of their research by reflecting on who they are collaborating with and whose voices are

– and are not – represented, who is designing the research and asking the questions, how the sources of research funding shape the research process, what science is being done and remains ‘undone’ (e.g. Frickel et al., 2010), and who will benefit from it.

6.2.4. Critical Air Quality Science

We intend for CAQS to serve as a way not only to bring the social and natural sciences together to “explode our vision of how things work, why environmental systems function the way they do…”, but also to clarify “how we […] can become more critically engaged with influencing or changing these interactions” (Urban, 2018: 61). As such, the combination of tenets proposed in CAQS can help to produce an air quality science ecology whereby new forms of evidence and altered conditions by which evidences of harm can take hold are co-produced (Gabrys, 2017; Stengers, 2011). Figure 6.1 is a heuristic for how CAQS can provide a more holistic understanding of air quality. It visualises three main nodes for different areas of research: knowledge politics, material ‘airscapes’, and social dynamics. The figure shows how material and social factors draw upon one another in their co-production, and how they both influence air quality knowledge production (Jasanoff, 2004). On the lines intersecting these nodes are the combinations of tenets taken from CPG, that are best mobilised to investigate the relationships between the nodes.

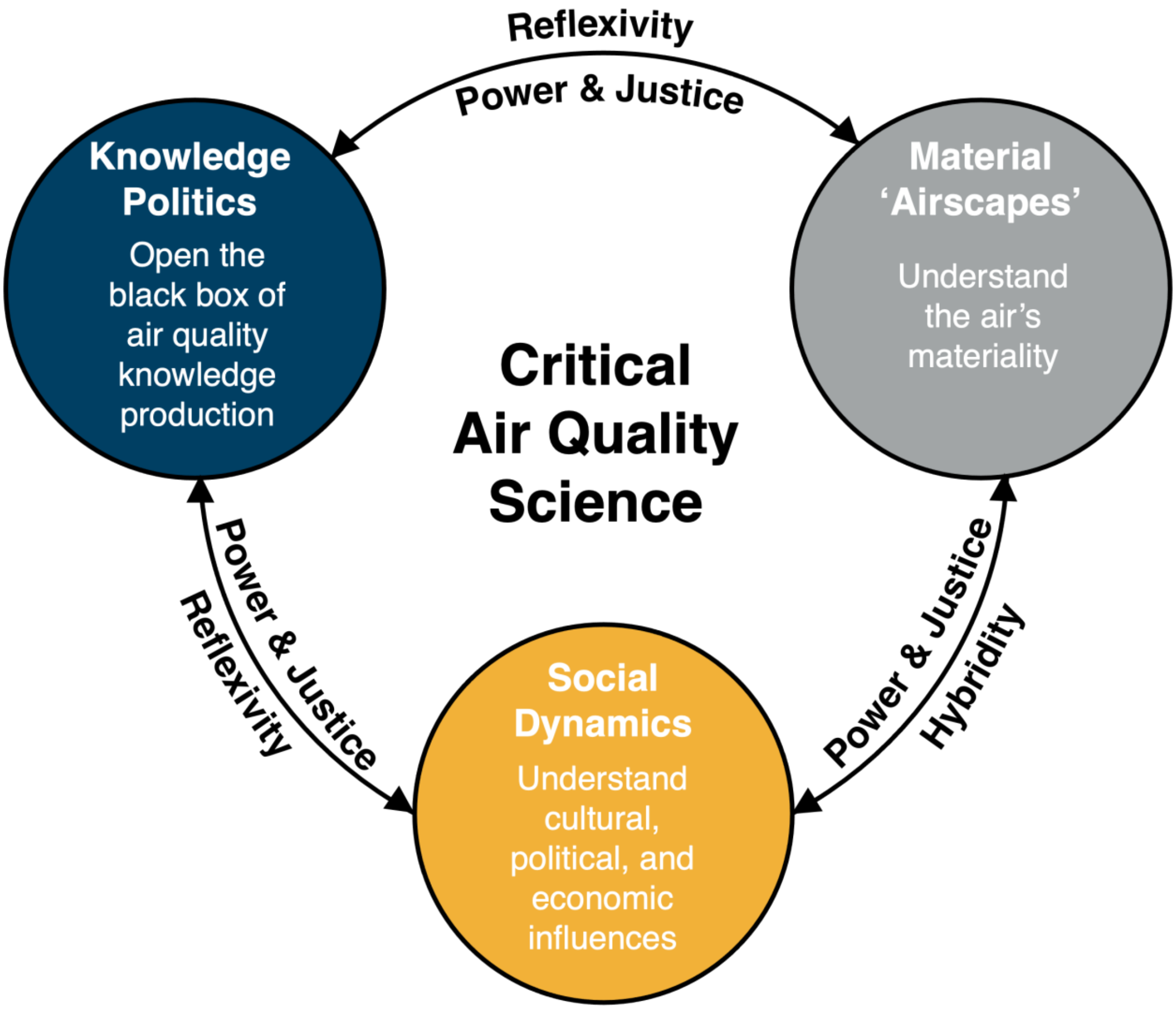

Figure 6.1: Critical Air Quality Science, depicting the three main areas of research required for a holistic understanding of air quality (knowledge politics, social dynamics, and material airscapes), and the tenets that can guide research methods between research areas (hybridity, reflexivity, power & justice).

While this provides a framework for guiding how undertaking CAQS should be approached, here we use it to inform our reflections on a citizen science air quality monitoring project that aimed to open up the process of knowledge production, but in ways that exposed tensions in how this materialised in practice. There are a wealth of different terminologies used to describe public participation in science (Strasser et al., 2019). We use the term 'citizen science' here as it is the most widely understood term, and encompasses an extensive variety of practices. In doing so though, we neither wish to diminish important debates around how terminology can include or exclude ideas, activities, or people (Eitzel et al., 2017), nor distance ourselves from other terminologies, but to be in dialogue with them. In the next section we explain more about this project and the data we draw on.

6.3. Materials and Methods

6.3.1. Study Site

Our study was situated in the Old Swan ward of Liverpool, UK, which is centred on the intersection of intra- and inter-city roads. Liverpool has been consistently ranked as one of the most deprived local authorities in England according to the Indices of Deprivation (National Statistics, 2019), which include deprivation variables for the 'living environment' that measure the quality of the indoor and outdoor local environment, including housing and air quality. Old Swan is a relatively disadvantaged ward within Liverpool, including for the quality of the living environment (Liverpool City Council, 2019, 2021). Our study was part of the wider Neighbourhood Resilience Programme (NRP) funded by the National Institute for Health Research Collaboration for Leadership in Applied Health Research and Care in the North West Coast area of England (NIHR CLAHRC-NWC), which looked to address health inequalities in areas experiencing social and health disadvantages by tackling their root causes. Public and patient involvement in research is at the heart of NIHR CLAHRC-NWC (Ward et al., 2020). To facilitate this, the NRP was set up to support capacity building between residents, businesses, and a range of professionals working in these areas to build 'system resilience', and Old Swan was one of those areas. Organised consultations and research activities with local stakeholders – including professionals working in the area and members of the public – led to the creation of the group Better Old Swan (BOS).

It soon became clear that the major arterial roads that cut through Old Swan and the effects of heavy traffic on air quality was an area of concern for BOS. Old Swan has no government air quality monitoring station and instead air quality is estimated from model simulations. This reliance on modelling was challenged by members of BOS, and has been observed in other community groups, who question models' underlying assumptions and compatibility with their 'local knowledge.' For example, models may fail to capture the hyperlocal air pollution that people experience as they move around urban environments, such as by cyclists in bus lanes (Yearley, 1999, 2006). BOS wanted to generate its own air quality data to demonstrate their perceived problem of traffic air pollution by measuring near schools and key routes in Old Swan. CLAHRC-

NWC brought the authors in to help facilitate a citizen science (CS) project to measure air pollution. To be clear, this was a pre-existing project that the authors contributed to, meaning that we did not design the project from the ground up. As such, it was not developed as an 'idealised' version of CAQS but rather provides an opportunity to reflect on the approach and the challenges in practice that transdisciplinary research collaborations can entail. It also provides a perspective from a minimally-resourced and more 'pragmatic' community-based project when compared to others, including some notable transdisciplinary environmental collaborations (e.g. OxAir, 2021; Whatmore and Landström, 2011). We refer to our collaboration with BOS in the third person as the group existed before our involvement and they were involved in other activities beyond campaigning for better air quality. However, we do use possessive references when relating to our own direct inputs (e.g. 'our coding'), and areas where the process was collaborative (e.g. 'we made measurements').

6.3.2. Data Collection and Analysis

In 2019, we teamed up with BOS to design and implement an air quality monitoring project using devices designed and developed by the lead author's company.[30] BOS designated responsibility to the lead author for the functioning of the air quality monitors, both due to complex operating procedures, but also BOS members' own time constraints to learn how to use them. In our case, doing undone science paradoxically required the use of a less accessible device, with a more complicated operating mechanism. However, as Froeling (2021: 8) argues, "CS does not imply that projects need to use low-cost sensors, it suggests rendering monitoring practices more accessible to citizens." We measured ultrafine particles (UFPs) indoors and outdoors, an unregulated air pollutant in worldwide air quality standards that are primarily emitted by road vehicles in urban environments, and vary greatly in space and time (AQEG, 2018). UFPs measurements were made to investigate both the main author and BOS's concerns about traffic air pollution from outdoors finding its way indoors. Concentrations of UFPs tend to be greater in urban areas due to a greater density of vehicles (Kumar et al., 2014), and indoor environments near busy roads

[30] This is a small business, set up with the aim to raise awareness of indoor air quality through the development of monitoring technologies and testing services, in close interaction with academic research communities.

have been found to experience significant concentrations of outdoor generated UFPs (Zhu et al., 2005).

We conducted 5 semi-structured interviews with members of BOS who had been involved in the air quality monitoring project to understand how they understood and aimed to use this air quality data. We used semi-structured interviews to remain close to the authors' interests, but also to be responsive to the interests and concerns of the interviewees as they make sense of the air (Bryman, 2008). While the project participants varied by sociodemographic characteristics including gender, age, profession, and educational attainment, their number was not great enough to draw conclusions about the relationship between their backgrounds and how they approached the CS project (e.g. Pateman, Dyke, and West, 2021). The views represented by the research participants are their individual opinions rather than the views of the wider BOS stakeholder group. The main author conducted the interviews, which were audio recorded and transcribed. On occasion we use research participants verbatim words or phrases in prose to better express their feelings. These are not explicitly referenced but are italicized to smooth the reading experience and to clearly differentiate them from the authors' interpretations. We completed a line-by-line open initial coding of the data followed by grouping them thematically, with themes that emerged from the data being agreed by the authors (Saldana, 2009). Our coding strategy was open to emerging themes addressed by participants and the authors' interest in the process of CS in action. This included tensions in the dynamics of knowledge production, the role of technical expertise (and scientific instruments), impacts on epistemic justice, and the politics of CS. We also draw upon our experiences from interactions with BOS members through group meetings and one-to-one interactions (including installation of monitoring equipment and group data analysis), and the reflections of the authors involved in the project.

6.4. Tensions in the Better Old Swan project

In this section we interrogate the four main tensions that emerged from our coding and data analysis. We then discuss the implications of these tensions for the practice of CAQS and reflect on how to address them when undertaking future CAQS work.

6.4.1. Making the doing of undone science matter in policy and practice

In this section we focus on how citizens – through doing undone science – can challenge dominant modes of knowing the air, and in doing so we reflect on some of the tensions not just in how CS can slot into established policy processes, but also in how the policy process can make the most of CS (Irwin, 2021). The success or failure of CS projects to influence policy is argued to be a function of its compatibilities with policy norms around data quality and management, organisation and governance, and alignment with current policy structures and agendas (Hecker et al., 2019). Mahajan et al. (2022) outline the science-policy-society interface for air quality CS specifically, detailing the range of different ways that citizens have attempted to translate data into policy outcomes.

The air quality data that we generated with BOS did not align with dominant ways of understanding and managing air quality in Old Swan, which focuses on measuring certain pollutants in certain spaces at certain temporal resolutions in order to meet required obligations for delivering policy objectives (Irwin, 2021). The project attempted to remedy undone science in Old Swan in four ways. Firstly, we held a workshop with BOS group members to decide air quality measurement locations that were important to them, considering the lack of government air quality monitoring station in the area, traffic patterns, social use of the space, and potentially negative effects of findings in chosen locations. Secondly, we decided at this workshop to measure UFPs, a key component of traffic air pollution that varies significantly in space and time, and is hypothesized to be more 'toxic' than larger particle sizes that are covered by air quality regulations (e.g. $PM_{2.5}$ and PM_{10}) (HEI, 2013). UFPs are unregulated in air quality standards worldwide, but their emissions from vehicle tailpipes are regulated, a disconnect due in part to scarce evidence of UFPs health effects, itself due to the lack of systematic measurements. This contrasts with knowledge on the health effects of legacy air pollutants such as $PM_{2.5}$ and PM_{10} that is far more established. This contradiction highlights fractured decision making over what is worth measuring and illustrates how power relations operate to decide what is harmful. Thirdly, we made measurements of both indoor and outdoor air quality to help BOS create a narrative around outdoor air pollution coming into the indoor environment. Indoor air quality remains a comparatively undone science (Grandia, 2020), receiving far less attention than outdoor air quality despite a significant portion of people spending the majority of their time indoors, and BOS participants were concerned about this. Lastly, we focused on short-term ‘spikes’ of air pollution in Old Swan to reflect exposures at specific times of the day, rather than the longer-term averages typical of air quality regulations.

In creating these data and attempting to use them to further dialogues with policy makers and practitioners, BOS groups members lamented that “*there are no obvious ways for local projects to work with the council.*” Moreover, when one of our colleagues from the CLAHRC-NWC contacted public health officers with the results of our study the Public Health Officer claimed of our air quality data that they had “*nowhere to use this*.” The concept of a ‘Catch-22’ was famously raised in the 1961 eponymous novel by Joseph Heller to capture a problematic situation whose solution has mutually conflicting or dependent conditions. This plagues action to remedy undone science, as in order to be seen as legitimate to decision makers, community groups must adopt many of science’s epistemic norms, values, and framings to construct their claims (e.g. Ottinger, 2010). This raises the question of how one can make the doing of undone science – particularly that which is locally situated and designed by those affected – matter in policy and practice.

Ottinger (2016: 99) argues that “where social movement-based citizen scientists align themselves with expert practices for the sake of scientific legitimacy, their critiques of standard scientific practices are apt to get lost.” Despite focusing on an unregulated pollutant with a tight spatial and temporal resolution, we did align with expert practices by using a regulatory compliant technique for measuring UFPs taken from vehicle emissions legislation. This acted as a ‘boundary bridge’ to make the results more credible and difficult to dispute (Ottinger, 2010). However, it is important to consider which standards are being used; using an ‘expert’ informational structure to gain legitimacy may not translate between different groups of experts, as in the case with BOS with the difference between air quality and emissions knowledges.

Moreover, simply following regulatory practices could shut down the possibilities that citizen monitoring opens up to generate forms of evidence that match their experiences (Gabrys, Pritchard, and Barratt, 2016). For BOS, we were interested in showing the effects on indoor and outdoor air quality of short-term spikes of vehicle emissions during school drop off and pick up. Indeed, one resident stated that the second-by-second UFPs data showed "*that even one vehicle could cause a peak…*" and that "*not one of these peaks should be ignored or discounted.*"

Another way to approach this tension of making the doing of undone science matter in policy and practice is to start from a position of the purpose of the research. Our project aimed to raise awareness of air pollution with residents, galvanise new members to join BOS, and start conversations with local stakeholders to help change the sociomaterial conditions that drive air pollution in Old Swan. Gabrys, Pritchard, and Barratt (2016) mobilise the term 'just good enough data' to explain the way in which data generated by citizens, alongside observations and experiences, can be used to create different forms of evidence that bring their experiences into spaces of recognition and relevance. Rather than aiming to replicate the standard scientific and regulatory practices, which arrive at a numerical value for the air pollution concentration, citizen data can indicate patterns about when and where air pollution might be occurring, and if it is related to particular emissions sources (Gabrys Pritchard, and Barratt, 2016). These air pollution episodes in space and time may not be visible under regulatory monitoring regimes, and citizen data can be used to evidence air pollution can harm outside of the standard environmental regulations and policy, and to start a process of public conversation or collective exploration into the problem.

The concept of undone science is of particular importance for CAQS as it confronts how scientific and regulatory definitions of what counts as air pollution have neglected – and continue to neglect – the concerns of certain communities, both by constraining citizens understanding of their own environment and shaping how citizens must speak so that they are heard by those with power (Ottinger, 2017a). There is not a simple answer for making the doing of undone science matter in policy and practice. However, critical air quality scientists should be mindful of this dilemma as they design and carry out research, with a particular focus on 'who' the research is for and its purpose.

6.4.2. Contesting "Insiderness" and "Outsiderness"

Community groups' knowledges are often framed as 'non-expert', 'insider', 'lay', or 'practical', based on their subjective beliefs and experience, or an embodied illness experience (Altman et al., 2008; Bickerstaff and Walker, 2003). Conversely, 'outsider' or 'expert' knowledge is associated with scientific and rigorous objective reason, based on 'hard' data and facts. (Naples, 1996). We are of the view that inside and outside are not fixed or static positions but instead shifting and permeable social locations (Naples, 1996), and that CAQS should challenge assumptions about 'insiderness' and 'outsiderness'. Our data shows how community groups and scientists can share similarities in the way they construct knowledge, and how they can transcend typical insider or outsider designations.

In addition to BOS's participants local knowledge of the area, including hotspots of air pollution, emission sources, and history of urban planning, they also understood the air in Old Swan through their sensory perceptions of smell, taste, sight, and hearing:

> There is a lot of noise, and the air does taste a bit funny around Prescott Road, and you can definitely smell that there's roads and vehicles around (Participant 3).

> There [are] days when in the summer when we don't have the rain and stuff like that where if the door is left open you can actually feel the grit on the floor. You can feel it coming in, on the tables and stuff like that (Participant 5).

Discussions also showed their knowledge of the air was through an embodied corporeal experience of coughing, choking, increased asthma and hay fever symptoms, and feeling "*chesty*":

> I often cough and choke when I am walking along the road […] when you're walking along and 5 or 6 buses come past together which are they are prone to do, and a couple of lorries […] (Participant 1).

However, to limit BOS's understandings of the air to these 'lay' ways of knowing would be to do them a disservice. They also demonstrated ways of knowing that are associated with traditional ‘scientific’ knowledge including observation, quantification, and linking to epidemiological research on incidences of health problems in the area. For instance, members of BOS linked their embodied experience of asthma symptoms with epidemiological research to explain incidences of asthma in the ward and family:

> Both of my children have been hospitalised with asthma when they were primary school age […] We know it is partly genetic because other members of my husband’s side of the family also have asthma. However, since I moved to Liverpool there is so much more research now that I think I would be foolish to put it just down to genetics. I think it would be quite ignorant of me to do that (Participant 2).

Moreover, BOS group members were keen on an approach that would link measured air pollution concentrations to health effects data from Alder Hey, the local Children’s Hospital:

> There is a lot of people collecting data at Alder Hey for different purposes […] Maybe they could provide information on incidences of childhood respiratory diseases and link that into your data (Participant 1).

This is an example of residents wanting to use parts of the technoscientific system to build their claims, which at least suggest they are aware of the value of some parts of the relevant expert knowledge infrastructures (e.g. Gabrys, Pritchard, & Barratt, 2016; Ottinger, 2010). We also do not wish to portray community members as universally having a deep inside knowledge of their conditions. Indeed, the construction of air quality as a problem recognised by ‘insiders’ only happens if air pollution is already seen as a matter of concern (Latour, 2004). In the project community members did have some prior knowledge of air pollution. However, it was not until they engaged with the Neighbourhood Resilience Programme (NRP) that they fully made sense of the effects that air quality was having on their lives. For example, in this participant’s account the information provided by an NRP workshop was consequential for their awareness that air quality was an issue:

> Once we actually found out the information, I was shocked, I was overwhelmed, how it’s affecting us […] once we got the information from

> the NHS about the elderly and the young people, and COPDs [chronic obstructive pulmonary disease], and the lung diseases (Participant 5).

Moreover, to refer simply to insiders and outsiders is to deny the heterogeneity of different groups. For example, BOS's make up was diverse in terms of education, life, and professional experiences and so on. The implications of assuming that citizens are non-experts poses the risk of designing methods of data collection that do not consider power dynamics within community groups, such as by only documenting the experiences of 'formal' local stakeholders, only documenting the experiences of 'informal' (lay) stakeholders, or mixing them in focus groups, which can alienate those who are less powerful or vocal.

The insider/outsider tension indicates that one should not underestimate the knowledge that a community might have. The construction of who is considered an 'insider' and 'outsider' is another manifestation of air pollution's hybridity. Managing discourses of 'insiderness' and 'outsiderness' is relevant for CAQS as they hold consequences for social processes that shape inequalities (Naples, 1996), by serving to legitimate and "control who fe[els] entitled to speak out and who c[an] be trusted to hear" (Naples, 1996: 102). Therefore, aiming to construct an environmentally just CAQS requires careful thinking to not reinforce problematic social processes, with the dichotomy between who is considered an insider/outsider as one of the most obvious examples of how particular forms of knowledge are construed and legitimated.

6.4.3. Traffic as both life and death

Traffic, "*the standing traffic that's just a killer*", was frequently referred to as "*the most obvious*" source of air pollution in the neighbourhood. At the same time residents also recognised that this "*killer*" was a significant source of life, through its associations with bringing people – and their money – into Old Swan to use its local businesses. One resident neatly encapsulated this tension when asked how this project will improve air quality in Old Swan:

> If you can get them to reduce the amount of traffic coming through the area. How they are going to do that without having a negative impact on the economy of the area, I don't know […] what Old Swan doesn't need is less people coming

> here as if you take any action which impacts on traffic then it will impact on people coming here and using the shops (Participant 1).

This tension highlights how air pollution's hybridity embroils it in other societal questions and disputes: from safeguarding jobs, to how we should heat our homes, and travel around towns and cities. The inextricable intertwining of air pollution's social and material components have been shown to obfuscate attempts to reduce air pollution's effects (e.g. Gramaglia, 2014), and it challenged members of BOS about what form an appropriate strategy for improving air quality in the neighbourhood would take.

Given that one of BOS's main objectives was to raise awareness of air pollution in the neighbourhood to inform effective structural solutions to address its root causes, it became a point of contention for BOS about how to communicate both the purpose and results of the CS project. There was a split between a desire to frame it in a more positive and optimistic note, versus a more realist approach aimed at frightening people into action. For the latter, one BOS member noted the difference between Liverpool City Council's public health campaign for air pollution (Liverpool City Council, 2018), and one warning about skin cancer from sun beds (We Are Brave, 2013), bemoaning that while the skin cancer advertisements were graphic and disturbing, in the air pollution posters "*the fumes are a pretty shade of pink: are these dangers a fairy-tale?*" This difference in messaging was particularly striking when a BOS member pointed to evidence that more people died prematurely from exposure to air pollution in Liverpool than were diagnosed with skin cancer. This formed part of some BOS member's argument for an approach that should deploy scare tactics to drive action against air pollution as they argued that "*nothing else but fear or money motivates change*." In contrast, another participant suggested that "*indignation changes nothing but your blood pressure*", believing it is better to "*light a positive candle and communicate that to people than the […] attitude of despair and indifference and denial*."

Confronting these tensions when reporting results is important for practicing CAQS, as any research can have sociomaterial impacts and consequences. CAQS seeks to consider who benefits from the knowledge produced and who will be harmed. As BOS members alluded, the way research is reported and disseminated can lead to measurable psycho-social impacts from feeling they are living in a 'risky' area (Bickerstaff, 2004), inadvertently perpetuating negative stereotypes, exacerbating stigma, and leading to other forms of miscrecognition (Law, 2018). Compounding the stigma of those living in areas of poor air quality may influence how they are treated by further designating their environment as 'dirty'. This can be a factor in political decisions over who is then chosen as an appropriate recipient of certain land uses, whether that be the siting of a new industrial facility or the building of a busy road, which in turn further exacerbates air pollution concentrations (Walker, 2009). The reporting and dissemination of air quality research needs to help communities achieve their goals, but should not contribute to negative stereotypes and stigma, unwittingly increasing inequalities.

To combat this, the way results are presented should locate problems in the conditions in which people live or work rather than as characteristics of individuals or groups. In doing so, you do not place the burden of pollution on those who suffer from it but allocate responsibility to the structural sources of pollution. This approach can help to reduce stigma and prevent reproducing stereotypes. For example "air pollution is high in Old Swan" could be reframed as "those living on the arterial roads of Old Swan suffer from higher traffic air pollution." However, there is still the concern that a form of realist communication might cause those with the economic means to "*run to the hills"* and leave Old Swan for the *"nice leafy suburbs."*

6.4.4. Changing behaviours or changing systems? Reducing air pollution vs reducing exposure

In the project BOS members were torn between investing efforts to promote behavioural changes to reduce emissions and exposure in the short-term, and longer-term efforts to ultimately improve air quality by challenging the wider system underpinning patterns of exposure. Most air quality research projects with communities are framed with the former in mind, and are constructed as a data collecting exercise to make visible 'hotspots' of air pollution, and to provide that information to residents so that they can change their behaviours to reduce their emissions and exposures (see Riley et al., 2021).

The tension here relates to how CAQS can balance short and long-term environmental justice objectives. Air pollution is damaging health in the short-term, but the current dominant focus on behavioural change does little to challenge its root causes. Moreover, research framed in behaviouralist terms might influence socioecological imaginaries by locating the responsibility for mitigating air pollution onto the individual. Instead, CAQS should work to create new imaginations that also challenge the root causes of air pollution. As imaginaries are 'world making' and structure policy, values, and norms, considering how they are influenced is crucial for CAQS (Gross, Buchann, and Sané, 2019).

In general, BOS members hoped that new awareness of the health effects and sources of air pollution following the project might lead to less polluting activities and reduced exposures for residents of Old Swan, as they are "*ultimately down to the individual*." This hope aligned with the narrative of a local public health campaign advocating for behavioural changes such as buying a less polluting vehicle, driving more smoothly, not idling, walking to school, parking away from schools and nurseries, and taking public transport (Liverpool City Council, 2018). While this approach was seen as necessary, residents were aware that it could become a 'quick fix' and insufficient for tackling the larger structural causes of air pollution. As one resident questioned, "*[is] the solution is to keep away rather than reduce emissions?*"

To manage this dichotomous traditional way of addressing air pollution, BOS developed an animation aimed to raise awareness of air pollution in the area so that other residents could both minimise their exposure and reduce their emissions, and begin building the connections with other local stakeholders that might help change the system, and fix air quality problems at the root (Porroche-Escudero et al., 2020). BOS members' understanding of systems change included funding transport infrastructure, including cycling, electric buses, electric vehicle incentives and charging points, and unearthing old tramlines, as well as the possibility of confronting major haulers and the firms responsible for rerouting traffic. Discussions about individual responsibility versus structural issues were also reflected in discussions between indoor and outdoor air quality: multiple BOS members said that fixing outdoor air quality should be the main focus, primarily due to the fact that they believe that the individual can make changes within their own indoor environment to improve the air quality, unlike outside where they are more reliant on structural changes.

Research that is focused on behavioural changes to reduce personal emissions and exposures is of course valuable. For example, it can mean less exposure to a vulnerable individual going to school by walking on alternative routes that are less polluted. However, we argue that an approach that focuses on this alone is akin to forever treating symptoms rather than the root cause. Moreover, it fails to recognise that many behaviour changes advocated to reduce air pollution can only take place once the right material and social structures are in place: whether that be cycling infrastructure, affordable public transport, or the time to use them (Riley et al., 2021). CAQS should consider its sociomaterial impacts and help to drive a shift in vision from individual behaviour changes to system change. This is important as visions of what air quality futures are possible structure societal understandings of agency and responsibility for poor air pollution, and who will – and will not – benefit from new air quality policies (Gross, Buchann, and Sané, 2019). However, more environmental justice research is needed in this space to theorize modes of justice that can be applied to dealing simultaneously with short- and long-term protections against air pollution.

6.5. Citizen Science and Critical Air Quality Science

In this section we focus on the broader discussions related to our case on the compatibilities between citizen science (CS) and CAQS. The analytical purchase provided by the development of CAQS has illuminated important tensions, contestations, and dilemmas in CS research. For BOS that included considerations related to how air quality research was designed, carried out, and communicated. To be clear, we are not saying that doing CAQS necessitates doing CS. However, it is a timely opportunity to reflect on the wider opportunities and challenges of doing them together, especially as CS methodologies are increasingly being applied to manage and better understand air quality. This includes providing low-cost air quality sensors to citizens (e.g. EEA, 2019) to facilitate breakthroughs in spatiotemporal understandings of air quality (e.g. Varaden et al., 2021), and to enhance public understanding of air pollution (e.g. Mahajan et al., 2020).

CS is often heralded to provide three main benefits: *democratising science* through wider stakeholder participation in decision-making, which reduces the likelihood of marginalising communities; *improving scientific literacy* to the scientific process; and *providing new scientific breakthroughs* made possible through massive citizen participation (Strasser et al., 2019). It is easy to see the potential links between CAQS's tenets of reflexivity and power and justice, and CS's *democratising science*: both aim to open the black box of knowledge production and reconfigure it with new knowledges in the pursuit of environmental justice. However, some have questioned whether CS necessarily leads to environmental justice (e.g. Davies and Mah, 2020) since alternative knowledges often remain absent (Bidwell, 2009). Moreover, CS initiatives do not universally promote traditionally marginalised voices, with biases by age, sex, ethnicity, and socio-economic status (e.g. Pateman, Dyke, and West, 2021), something that was noticeable during the project despite our best efforts.

CS represents a wide range of practices from citizens contributing data to standard scientific practices, to being involved in all stages of the research (Haklay, 2013). The type of CS enacted, who it is involving, and ultimately who the research is for, significantly affects the compatibilities between CS and CAQS. These points can be addressed when looking at the genealogy of CS, which has two distinct meanings (Cooper and Lewenstein, 2016): 1) as a science that both assists the needs and concerns of citizens, and that is developed and enacted by citizens themselves (Irwin, 1995); and 2) as a science where non-scientists can voluntarily contribute data to scientific projects (Bonney, 1996).

These different typologies of CS affect the potential for CS and CAQS compatibility around claims of improving scientific literacy and providing new scientific breakthroughs. For example, equipping non-scientists with air quality monitors to educate them on the process of generating air quality data might help with improving non-scientist literacy. Likewise, it might help to provide new scientific breakthroughs related to higher spatiotemporal resolution understandings of air pollution. Both claims could be made about our project with BOS. However, "not even the strongest sensor with the highest-resolution open-source real-time data will be enough to magically manifest environmental justice, especially if that injustice is built on a firm foundation of inequality and oppression" (Davies and Mah, 2020: 239). We do not want an approach focused just on the gathering of more, 'better' data, but instead an approach that sees improving scientific literacy as a two-way street, where scientists and non-scientists learn from each other. Therefore, it was particularly important for our collaboration with BOS to focus on air quality's sociomateriality. This can also be illustrated by partnerships between citizens and local councils where citizens contribute local knowledge in participatory modelling activities to make models more robust, by ensuring that model inputs and assumptions are correct, and the priorities of research are in the right place (e.g. Yearley, 2006). Beyond just improving the accuracy of scientific models, these local knowledges can also improve scientific literacy and create 'data citizenships' that promote more democratic engagements with environmental data (Gabrys, Pritchard, and Barratt, 2016).

There is not a one-size-fits-all CS, nor a universal CS that is suitable for CAQS. However, there are significant areas where they can coalesce or collide dependent upon the form of CS that is undertaken. A CS approach where non-scientists can voluntarily contribute data to scientific projects might be helpful in certain circumstances. Similarly, an approach that assists the needs and concerns of citizens, and that is developed and enacted by citizens themselves can also be productive. For CAQS a blend of the above would be ideal, where scientists and citizens work together to understand and reconfigure material landscapes, social dynamics, and knowledge politics.

6.6. Conclusion

Air pollution is a hybrid phenomenon, known and produced through social practices *and* environmental processes. Understanding air pollution in this way requires careful consideration of how air quality science is done. This is especially true in a context which is increasingly embracing citizen science (CS), including through the deployment of low-cost sensors, and participatory monitoring and modelling practices, which challenge dominant scientific paradigms. In this paper we combined a theoretical argument with reflections and data from interviews with citizen scientists during a collaborative air quality monitoring project. In dialogue with critical physical geography's core tenets, we proposed Critical Air Quality Science (CAQS) as a provocation to think through air quality science in a hybrid way. Using this framework, we illuminated important tensions in CS research. The first tension ‘Making the doing of undone science matter in policy and practice’ highlighted the challenge of designing air quality research that is valuable to different sectors of society. We showed that this involves balancing alignment with expert practices and informational structures versus maintaining an element of critique by recognising and incorporating alternative knowledges. We recommended that practitioners should remember who their studies are *for* when doing CAQS. The second tension ‘Contesting “Insiderness” and “Outsiderness”’ argued that inside and outside are not fixed or static positions. We reflected on how stakeholder knowledges are construed and legitimated in transdisciplinary research, and their implications for the design and reporting of air quality research. The third tension ‘Traffic as both life and death’ illustrated the sociomaterial impacts of how research is presented. We suggested that results should be presented so that they locate problems in the conditions in which people live or work rather than as characteristics of individuals or groups, and that the perspectives of those who are affected by air pollution should be prioritised to avoid adding to their problems. The final tension ‘Changing behaviours or changing systems? Reducing air pollution vs reducing exposure’ explored how citizen scientists can be faced with the dilemma of whether to focus on individual responsibility to minimise exposure, or structural issues aimed at reducing air pollution. We argued that this dilemma is shaped by – and shapes – potential air quality futures.

We have proposed CAQS as an attempt to reopen the conversation on how we can reconfigure air quality science to combine material and social concerns (e.g. Cupples, 2009). We envisage that by simultaneously opening the black box of air quality knowledge production, understanding the air’s materiality, and embracing social dynamics, CAQS can help to make sure that air quality science leads to appropriate sociomaterial interventions that do not exacerbate existing air inequalities.

7. Conclusion

In this thesis I have analysed, in sociomaterial terms, the production of air quality. I have explored how air quality knowledge is produced and critically engaged with how we can reconfigure our relations with the air to begin to address air inequalities. I did this by drawing upon my direct involvement in three different forms of doing air quality science. The three case studies that did different forms of air quality science were categorised using a postnormal science (PNS) heuristic, which groups science into three broad typologies: applied science (Paper 1), professional consultancy (Paper 2), and PNS (Paper 3). These typologies include epistemic (*system uncertainty*) and axiological (*decision stakes*) variables (as shown in Figure 1.1). In this final chapter I outline the contributions across the thesis, including specific contributions from the papers. I then answer the research questions that I laid out in the Introduction chapter, but also go beyond them to think through the further implications for different groups. I also relate the implications of my findings on constructing future diverse claims of EJ, before finishing the chapter with some suggestions for future research.

7.1. Key findings / contributions

In the Introduction chapter I outlined five wider contributions of this thesis. First, that through both doing air quality science (in new contexts such as citizen science and industry science), and later reflexively analysing the process (drawing upon my own multiple and shifting identities), I contribute a novel perspective investigating the mediating role of air quality science in the *production* of the air (e.g. Cupples, 2009; Garnett, 2015, 2017, 2020; Whitehead, 2009). Second, I directly answer Cupples's (2009) call for a hybrid reframing in air quality science: especially through using Actor-Network Theory (ANT). Third, and related to this hybridity, inspired by the critical physical geography (CPG) subdiscipline I develop a new critical air quality science (CAQS) framework to study the air's sociomateriality, providing a platform for further work to be done under the CPG or CAQS umbrella. Fourth, I contribute to the critical scholarship of indoor air quality (IAQ) through developing sociomaterial understandings of IAQ, both in terms of a hybrid framework, but also characterising its social and material elements which have both been under studied (AQEG, 2022; Biehler and Simon, 2010; Graham, 2015). Fifth, through focusing on my own mediating role in the doing of air quality science, I contribute to research investigating epistemic justice, which is an emerging aspect of environmental justice (EJ) scholarship. In the sections following I outline the findings and contributions from each of the papers, as well as reflect on their wider implications.

7.1.1. Paper 1: Applied science

In Paper 1, I looked at an example of applied science, a type of science with low systems uncertainties (the complexities of the system under consideration) which are managed at the technical level through standard operating procedures, and low decision stakes (the costs, benefits, and value commitments that are involved in the issue) as there is a clear use of the results (see Figure 1.1). Applied science in this instance took on the form of a PhD indoor and outdoor air quality monitoring project at a school in Lancaster.

In this paper I challenged my own ready made science (RMS) account of this applied science project. Through using a combination of reflexive and relational ethnographic approaches (labelled as an autoethnography) I interrogated my own multiple and shifting identities to make visible relations that are usually obscured during the doing and reporting of air quality science. I did so to identify areas where air quality scientists might adapt their practices to facilitate a more effective and equitable engagement on issues of air quality by probing what they are doing and why, and with what sociomaterial effects. To do this I both deployed ANT in a more a traditional form (e.g. Latour and Woolgar, 1979) to show my construction of the air by contrasting science in the making with RMS, but also through using the concept of ‘circulating reference’ (Latour, 1999) to show how scientific knowledge on the air is produced in a chain like manner: rather than directly reporting on a material reality, air quality knowledge moves from matter to form in a series of transformations (or links of a chain). Through elucidating this chain like circulation of scientific knowledge making, I highlighted the role of a variety of human and non-human actants that influenced the questions about air quality that the research asked, how they were investigated, and how the air was ultimately represented: this included the air pollutant that was measured (ultrafine particles – UFPs), the air quality monitor that was deployed (V2000), and my plural identities (as a PhD Researcher, and the CEO of the company that designed and makes the V2000). In focusing on these transformations from matter to form, I situated air quality science as a local achievement, with a wide range of contingencies. Moreover, I challenged some disciplinary categorisations of air quality *monitoring* and air quality *modelling,* showing that if you go deep enough there is always a model. This localised perspective on air quality knowledge production raises some tensions. Specifically related to how localised practices embed a certain set of relations with the air that ultimately informs our understanding of – and subsequent reaction to – air pollution. This begs the question of what is the appropriate role of science? How much of its internal workings can – and should be – black boxed? These are all points that I pick up later in this chapter.

7.1.2. Paper 2: Professional consultancy

In Paper 2, I looked at an example of professional consultancy, a type of science with moderate systems uncertainty which involves more complex parts of scientific problem-solving such as data reliability and the implications of its results, and moderate decisions stakes as the project was carried out for a client, bringing with it more value judgments. The professional consultancy in this instance took the form of a research-business project measuring IAQ to assess the effectiveness of an air cleaning device in 20 school classrooms around England and Wales.

In this paper I used a combination of reflexive and relational ethnographic approaches, drawing upon my own direct involvement in the professional consultancy, as well as other internal project documents to show the ways that the research was affected by the emergence of COVID-19. Using an approach that was 'near' ANT (Farías et al., 2020), a phrase I use to indicate a close allegiance to ANT but also other similar strands of social investigation, I demonstrated the sociomaterial instability of air pollution, as new material pollutants emerged (SARS-CoV-2), and social definitions of what it meant for the air to be polluted changed. Using this near-ANT approach, I both outlined the processes and practices that shaped sociomaterial relations indoors, but also drew upon the concept of 'matter of care' (Puig de la Bellacasa, 2011) to show

how the research was re-assembled because of COVID-19. This involved changing our approach from one focused on measuring the effectiveness of the air cleaner, to instead focusing on intervening to mitigate COVID-19. In doing so I contributed to conversations around ‘intervention’ (Zuiderent-Jerak and Jensen, 2007), ‘intravention’ (Estalella and Criado, 2018), and ANT positively intervening in social research (López-Gómez, 2020). Moreover, I related the project to wider implications for academia and practice, including questions of inequalities and responsibilities: points that I will again expand upon later in this chapter.

7.1.3. Paper 3: Postnormal science

In Paper 3, I looked at an example of postnormal science (PNS), a type of science with high systems uncertainties and decision stakes which means that uncertainties move beyond that of the system and become inseparably entangled in ethical dilemmas. In these postnormal situations, PNS calls for scientists to work with those that the problem is actually affecting to produce research that is relevant. The PNS in this instance took on the form of a citizen science (CS) air quality monitoring project with a community group in Liverpool called Better Old Swan (BOS).

In this paper, I combined the doing of air quality science that was relevant to BOS, with developing a CAQS framework to guide the simultaneous study of the air’s materiality and social dynamics: its hybridity. I also advocated for CAQS’s use as a framework for air quality scientists to meaningfully do hybrid air quality science. As such, I met Cupples’s (2009) call for science to take non-scientific knowledges seriously, and nurture an understanding of different knowledges in the creation of evidence against air pollution. I also used my CAQS framework alongside interviews with BOS citizen scientists to outline four tensions in the dynamics of CS knowledge production, including the impacts of how air quality science is designed and reported on EJ: making undone science matter, blurring “insiderness” / “outsiderness”, traffic as both life and death, and changing behaviours versus changing systems. I expand upon these tensions later in this chapter.

7.2. Research questions

In the Introduction chapter I posed three questions to guide my research into how knowledge of the air is produced, and how we might change our relation to the air to begin to address air inequalities. In this section I detail how I answered these questions in the papers that form the thesis, as well as provide some wider reflections.

7.2.1. Research question 1: How is knowledge about air quality produced and represented across different contexts and forms of air quality science? What dynamics and tensions emerge?

Throughout this thesis I have shown how knowledge of the air is produced and represented in different projects, and the dynamics and tensions that emerged in different places, and at different times.

In Paper 1, I showed that the air's production and representation is not a direct translation of a material nature. Instead, it is a local achievement, realised through a series of smaller transformations. In this paper I showed how in these transformations a variety of human and non-human actants had a mediating role. For example, I raised the specific tension related to my own goals and motivations as a PhD researcher. This included tensions related to my own desire to measure air *pollution* rather than air *quality* to satisfy the novelty required for a PhD. The implications of this are that an RMS account, even if only of an applied science, is not enough to explain how and why this form of science was done. Ultimately, it shows that in reality low uncertainty, low stakes issues (defined as applied science) have now all but vanished (Ravetz, 2010).

In Paper 2, I was operating in a context of extreme sociomaterial dynamism, with the air's production and representation being destabilised by the emergence of COVID-19. What came to count as air quality (or indeed air pollution) changed with a shift from focusing on the air's material constituents coming in from outside, to human emissions of airborne viral particles. Moreover, the air as a form of knowledge shifted with new inscriptions taking precedence to evidence the air's potential harm. In doing so we adapted our project to be more geared towards a matters of care ethic, designed to produce knowledge about the air more directly relevant for the schools' inhabitants, helping them to promote better IAQ for the immediate matter of concern of COVID-19. This did somewhat scupper some of the matters of fact that we were trying to develop around the efficacy of the air cleaner, as by increasing ventilation rates we were simultaneously minimising its effectiveness. This inadvertent matter of care ethic raised a tension for an IAQ science that solely measures what is known to be harmful, with less of a focus on improving IAQ or minimising exposure. This is not to say that IAQ currently is ambivalent to those affected. Indeed, cleaning up the air is a big goal of air quality science (Cupples, 2009). However, it often does not do so in a direct way, instead opting for an indirect approach of providing evidence to act. Indeed, these tensions form part of a wider discussion on the appropriate role of science in dealing with environmental harms.

In Paper 3, I outlined four tensions that emerged in the dynamics of CS knowledge production. The first tension, "making undone science matter in policy and practice", highlighted that citizens are often challenging dominant ways of knowing and assessing risks of air pollution, for example over short vs long term exposures. However, to be heard in the court of environmental disputes, citizens have to speak the language of those with power. This means that citizen scientists often have to adopt science's dominant framing to be heard: this represents somewhat of a catch-22. The second tension, "contesting "insiderness" and "outsiderness"", problematised who is considered a purveyor of accurate knowledge: insiders are often portrayed as having lay, subjective knowledge, and outsiders as having scientific, objective knowledge. The third tension, "traffic as both life and death", focused on the hybridity of air pollution, which does not simply exist out there, but is something that behaviours and societal structures create. In this case it manifested as traffic as the main source of air pollution in Old Swan, but also the main source of economic vitality. The fourth tension, "changing behaviours or changing systems? Reducing air pollution vs reducing exposure", explored how BOS were uncertain on whether to focus on the short-term goals of reducing emissions and exposure through focusing on behaviour changes, or a longer-term strategy aimed at improving air quality by challenging the structural causes of air pollution. The tension herein lies for how to balance short and long-term EJ objectives when air pollution has short-term health effects, but only focusing on these short-term exposures does little to challenges the root causes of air pollution.

Across the three papers, the different productions and representations of the air do ultimately raise some questions over the implications of understanding what is inside the black box of air quality science. First, how should one be reading and using air quality science when all of these transformations and actants are obscured in the process of doing and representing the air? To answer this question, I turn to some of the work of environmental sociologists during the so-called 'science wars' who highlight that a particular model of engagement is implicit in many critiques of socially constructed views of science (e.g. Jasanoff, 1996; Burningham and Cooper, 1999). Of course, when I have shown that other factors influenced the way that my indoor and outdoor air quality monitoring projects was carried out, I by no means intended to suggest that they were not still scientifically legitimate. The fact that this point even needs to be made is because science is often framed as needing to provide incontestable truths of the natural world. Therefore, it is argued that accounts that shown an element of social construction provide no contribution in managing environmental problems, rendering it as politically undesirable (e.g. Dunlap and Catton, 1994). Moreover that using an epistemology that references interpretive flexibility runs the risk of destroying reality (Burningham and Cooper, 1999). This dominant framing is difficult to escape when one is reading air quality science. However, I would argue that reading it from a hybrid perspective, that emphasizes its simultaneous material reality and social construction, offers an opportunity to not see any written text as an arbiter of an absolute truth, but as a situated and partial account, that may well still be the best available evidence. It is, therefore, an opportunity to think of the range of relations that might have influenced the way the research was done, and also the sociomaterial effects that the paper might have.

Second, what should scientists be doing differently? How much of the mess of science in the making should be reported? In recognising the heterogeneity of air quality science, it would be foolish of me to then offer a one-size-fits-all recommendation. Science is necessarily built upon black boxes, and I am not one to suggest that a full warts-and-all approach to reporting how the science was really done is required in all circumstances. However, I think it is worth scientists considering how they might do better science having reflected on the mediators that have been at work in their science. For example, through providing more information on some of the trials and tribulations of their methods, whether that be in the main body, or increasingly in the supplementary information of a journal article, it might help scientists to remedy the so called "reproducibility crisis" in science (e.g. Stoddart, 2016). Moreover, through making visible these relations, it might help scientists to think more clearly about who the research is for, and what its impacts might be. These are all points that I identify in my CAQS framework, which I hope can serve a heuristic for scientists from different backgrounds to work through these questions of how much (and what) information to provide.

7.2.2. Research question 2: What relations and legitimisation processes are embedded within different forms of air quality science? What are the impacts on addressing air inequalities?

Across this thesis I have shown an array of relations and legitimisation processes that are embedded within different forms of air quality science. Of course, I recognise that my papers represent but one example of air quality science for each typology in Figure 1.1, and that, therefore, they are not necessarily representative of that typology en masse. Notwithstanding this lack of generalisability, they offer some interesting insights.

In Paper 1, I highlighted the mediating role an array of humans and non-humans including, me and my multiple identities, the other creators of the V2000, the school site supervisor, the V2000 itself, calibration aerosols, working fluid, and UFPs. Through uncovering the embedded relations in the doing of air quality science, I highlighted the important role of metrology as a legitimisation process. Metrology, the science of measurement, ensured that in the project I measured the 'right' relations. That is, those defined by the metrological institutes, and the array of other standards, instruments, and institutions that they represent. Metrology allowed the measurements I made to be comparable across space and time, and therefore, become an immutable mobile. Of course this is not all just about ensuring accurate measurements, but also about creating a culture of regulation (Barry, 2002), and constructing a scientific apparatus for air governance (Whitehead, 2009). These legitimisation processes were also prevalent in Paper 2 and Paper 3, albeit in slightly different ways.

In Paper 2, Building Bulletin 101 (BB101), the UK Government advice document for schools on ventilation, thermal comfort, and IAQ became a prominent relation. BB101 was there in Paper 1 as an intermediary as I was measuring IAQ in a school after all. However, BB101 focuses on measuring CO_2 as an indicator of good IAQ, and in Paper 1 my focus was on UFPs rather than CO_2. Moreover, before COVID-19 BB101 was not a particularly forceful actant. It became much more important following COVID-19s enrolment, as CO_2 allowed us to measure the right relations: the relation between the air breathed out of humans – and their potential role in carrying airborne viral particles – leaving the classroom through ventilation. This difference between Paper 1 and Paper 2 in the role of BB101 was more circumstantial rather than evidence of an innate difference between applied science and professional consultancy. This strengthening of BB101 as a legitimisation process to govern IAQ differs from some of the roles that metrology has played across the chapters of the thesis. Rather than develop governance to permit the movement of immutable mobiles, the deployment of CO_2 sensors harboured a promotion of 'self-care': the inscriptions provided by CO_2 sensors aimed to condition building inhabitants to manage their own IAQ through enrolling an array of human and non-human actants to organise the relationship between the air indoors and outdoors. This was of course agnostic to how 'fresh' the air from outside is that is replacing potentially virus laden indoor air.

In Paper 3, through contrasting relations between non-expert/insider and expert/outsider knowledges, there were some similarities and substantial differences in its relations and legitimisation processes compared to Paper 1 and Paper 2. My CS project generated air quality data that fell outside of the usual practices of legitimisation and validation that characterise scientific data. Rather than aiming to replicate the regulatory methods and techniques for measuring air pollution, which arrives at a more accurate air pollution concentration, we aimed to indicate patterns about when and where air pollution might be occurring, and if it was related to particular emissions sources (Gabrys, Pritchard, and Barratt, 2016). The impacts of these relations and legitimisation processes on addressing air inequalities, was largely on its epistemic justice implications. In particular, hermeneutical injustice as the normal practices and frameworks for making sense of quantitative air quality data did not reflect local concerns and experiences, in conjunction with BOS struggling to invent new ways for making sense of the data that both reflects their experiences and was digestible to experts.

Across the three papers the air's governance, and its relations and legitimisations processes took on both some similar and different roles. Ventilation guidance, in particular BB101, was most relevant to my accounts in Paper 1 and Paper 2, albeit in the different ways that was previously described. The differences in the role of BB101 showed the shifting nature of some of the legitimisation processes governing school IAQ, and the role of a wider sociomaterial context (e.g. COVID-19 becoming a matter of concern). Metrology, as a legitimisation process was prevalent across all the papers, impacting air inequalities by defining a correct way of knowing the air. While this was relevant to all of the papers, it was most acutely felt in Paper 3, as my CS project fundamentally challenged some of the legitimisation process of air quality science (that were showcased in Paper 1 and Paper 2). In particular, it challenged what counts as relevant information: this includes what, where, and when to measure, and what devices and techniques can be used. This raised fundamental questions of what CS data can be used for, and how it can influence decision-making processes. By highlighting this tension, this is not a call to say that non-scientific knowledge should be given precedence over scientific knowledge, but rather that there must be alternative ways to evidence harm that extend beyond the relations and legitimisations processes of traditional air quality governance. For example, as I mention in Paper 3, data can be "just good enough" (Gabrys, Pritchard, and Barratt, 2016) to create different accounts and forms of evidence for engaging with environmental problems. This means that the role of scientific expertise in CS projects should not be to reinforce a deficit model of science that sees the public as there to be taught. Instead it should be there as a tool to push for 'undone' science' (Frickel et al., 2010), to facilitate the opening of closed policy processes, to fill knowledge gaps to show ongoing consent as local and scientific knowledge changes, and to ensure that scientists produce knowledge that is relevant to residents (Ottinger, 2013).

7.2.3. Research question 3: How can a hybrid approach to understanding air quality contribute to addressing air quality issues and inequalities effectively?

Both the natural and social sciences have contributed greatly to understanding air quality. Natural science, for example, has identified constituents of the air, how their concentrations change across space and time, and their effects on humans and non-humans. Activities that are all vital to underpin evidence-based policy to improve air quality and reduce exposures. However, despite a somewhat overwhelming amount of – quality – air quality science, people still die in great numbers because of exposure to air pollution. On the other hand, social science has contributed to, for example, understanding why polluting activities persist despite the natural science evidence, as well as showing the "texture" of science (e.g. Jasanoff, 1996) including its range of relations to other social, cultural, economic, and political domains that come to underpin what and how we come to know about the air. However, no matter how one socially defines that air, it still has undeniable material affects that need to be accounted for. In this thesis I have deployed an understanding of the air as both socially constructed and real: a hybrid entity that is tied together by material, social, cultural, economic, and political relations. By viewing the air's materiality, or it's material 'airscapes' (see Figure 6.1), as being co-produced by humans (and their structural inequalities) and the materiality of 'nature', I showed how knowledge of it is produced, and argued how it could be done so differently.

One of the main ways in which a hybrid approach to understanding air quality can contribute to addressing air quality issues is having an approach that simultaneously makes sure that the public understands the latest science, but also that the science understands the public. As Cupples (2009: 209) argues:

> *"This view is particularly pertinent to air pollution science, the motivation of which is to reduce air pollution by encouraging people to act. Air pollution science must then find an effective way to engage in a reciprocal and transdisciplinary dialogue with the social and cultural worlds in which science is embedded."*

A key part of air quality science's current proposition is that more, better information will lead to individual and system changes to address air quality issues. However, this has often proved not to be the case as air quality knowledges are not just related to the quantitative representations provided by air quality science, but are also wrapped up in other knowledges, including identity and sense of place (e.g. Cupples, Guyatt, and Pearce, 2007). Understanding this is critical to provide the full range of evidence required to understand why people act (or do not act) when presented with an abundance of evidence of air pollutions harms, and to encourage new ways of relating to the air.

This hybrid perspective also has large implications for addressing air inequalities. Through blurring nature/culture boundaries, dealing with air pollution moves from solely being a technical issue (which erases questions of power), to part of our environmental politics, as questions are asked about the role of those that produce representations of the air. Indeed, a hybrid approach facilitates conversations on the mediating role of air quality scientists in "not simply presenting the state of air pollution to us as it is" but also "intervening in how we might understand it" (Cupples, 2009: 213). It goes further than just understanding, as the way that scientists frame air pollution issues also frame the ways in which we can respond. Therefore, hybrid approaches represent opportunities for developing different relations to air quality science and governance that deal with "the multiple and contradictory ways in which air pollution is lived and experienced" (Cupples, 2009: 208), and might change the knowledge and priorities of the science system itself, making it more relevant to societal needs.

Taking up this dichotomy, in this thesis I brought the natural and social sciences together to both *do* air quality science and a *science of* air quality science. I did so to contribute to addressing air quality issues and inequalities by providing the material evidence of the concentrations of air pollution, but also doing research that was relevant to those that the air pollution was affecting, while being aware of my own mediating role. This is perhaps most clearly done in Paper 3 where I both defined a hybrid approach to doing air quality science (CAQS) but also helped BOS to make measurements to provide matters of fact that would contribute to them constructing air pollution as a matter of concern in their locality. In terms of the impacts on addressing air inequalities, through focusing on my own role in making certain relations to the air, I did identify tensions in CS air quality knowledge production that directly related to questions of epistemic justice. As such, I deployed an approach that attempted to develop different relations to air quality science and governance through doing CS that was "action-oriented" and focused on "implementing interventions, changing policy, or eliminating disparities" (Wilson et al., 2018: 285). This came from doing undone science (see Frickel et al., 2010), and opening up what might otherwise be closed policy processes.

In Paper 1 and Paper 2 I answered Cupples's (2009) call to use ANT as a way to do hybrid air quality science, and to contribute to addressing air quality issues and inequalities. I made visible the range of different relations that are obscured during the normal reporting of air quality science (and that constitute air pollution as a material reality), and also demonstrated air quality's sociomaterial instability. In Paper 1, alongside developing material understandings of the flows of UFPs indoors and outdoors at a school, I also mobilised my multiple identities and Latour's (1999) concept of circulating reference to show the many times and places during the process of doing air quality science that one could intervene to reimagine the relations that form and are formed by air quality science. In Paper 2, I not only provided material evidence of air pollution concentrations, in particular related to its role in transmitting COVID-19, but I also adapted the project along a matter of care ethic (Puig de la Bellacasa, 2011). Moreover, I looked at the patterned networks in which classroom IAQ is implicated and its potential effects. In particular, related to the reorganisation of classroom IAQ as a matter of personal care (Whitehead, 2009) following the deployment of hundreds of thousands of CO_2 sensors. These are all insights and developments that were made possible owing to deploying a hybrid approach.

7.3. Air quality and environmental justice: from identifying injustice to working towards justice

In this section I think through the implications of an epistemic framing of environmental justice (EJ) on constructing future EJ, including potential tensions with other claims of EJ. That is, what could more firmly centring whose knowledge comes to count in disputes about air quality mean for diverse claims of future EJ?

EJ has been a central part of the work in this PhD. I had originally planned to look at the distribution of air pollution *indoors*, to see how the wealth of research on outdoor air quality and EJ might relate to the air breathed in indoor environments. However, as I have previously said, it was during the process of doing air quality science, and further reading of science and technology studies (STS), critical physical geography (CPG), and EJ literatures that my focused shifted to the practices of air quality science. As such, I looked at my own role in the doing of air quality science, and its implications for questions of epistemic justice: that is, the extent to which people are respected in their capacity as knowers. I argued that this aspect of EJ is an especially important consideration for those practicing air quality science, as they play a key role in constructing and representing different groups' concerns about air pollution. This consideration largely came from my work with a citizen science (CS) group in Liverpool called Better Old Swan (BOS) where I noticed tensions in the different knowledges (e.g. expert and lay) that constitute claims of harm from air pollution, and potential injustices.

Identifying cases of current environmental injustice is a necessary but insufficient condition of achieving future EJ, as EJ claims need to mobilise public opinion and wider society to achieve change. This is the case as what can be considered as EJ is normative, and therefore is not a static entity, but one that is an active relational process that has to be worked towards. Indeed, in the literature review I introduced some of the ways in which justice was attempting to be done including the role of CS, low-cost air quality sensors, and data. My work with BOS was framed around a sensitivity towards epistemic justice. In my project I argued that democratising participation in science to help affected communities – without a voice in campaigning for change – to do science that was 'relevant' to them was a way of achieving a more just air quality arrangement. It is clear that in my logic at the time was an implicit view that maximising the inclusion of voices in air quality science and governance was a way of maximising EJ, and that CS can be a model of doing so. However, in this view there are a few challenges for moving towards a future EJ. It is worth considering whether citizens' understandings are necessarily superior to those of scientists (or experts)? And whether maximising the representation of voices necessarily lead to better air quality, or a fairer share of air pollution?

CS is often taken uncritically as a noble and worthy scientific approach (Riesch and Potter, 2014). It is argued that people know their problems, and science should help them to work towards solving them. However, modern issues of air pollution are often much less perceivable than in the past. Long gone are the days of the ‘pea-souper’ smogs (in the UK at least), as concentrations for most air pollutants have substantially decreased over the past few decades (albeit not a pace that has outstripped evidence of air pollution’s harms!). Therefore, claims of EJ are more reliant than ever on the foundational science that has been done to create matters of fact that communities can then mobilise as a matter of concern. This includes what pollutants are of concern, what levels can be deemed ‘safe’, and what the dominant sources are. Indeed, I saw this tension in my work with BOS where air pollution had retrospectively always been a concern for the community falling under a more general problem of ‘traffic’. However, air pollution itself only became a matter of concern in a way that could be mobilised once the ‘facts’ were given to them through the research project. As such, this does a raise a tension that doing air quality science to maximise an epistemic justice framing of EJ, and therefore to increase the inclusion of different knowledges, might invariably reduce some of the immediately ‘less relevant’ foundational science done in that locality. These different modes of science are not necessarily mutually exclusive, as sympathetic scientists can carry out primary research that has been co-produced by an affected community. However, it could still be argued that an EJ focused on representation of voices and knowledges alone could, in the long run, lead to poorer EJ outcomes based on distribution. This is because scientific evidence, which currently is the foundation of evidence-based policy making, may not be generated to evidence (and call for action to reduce) hot-spots of air pollution that coalesce in certain areas. Instead, through research projects focusing on democratising participation in making meaning of air pollution, it could further complicate what should even be considered as air pollution in the first place, for better or for worse.

In a sense, this necessitates that neither citizen or expert knowledge should be universally and uncritically privileged. The key question is if all forms of knowledge are a claim to authority in some way, what is the appropriate balance of knowledges? This is a challenging question, and one that I struggled with in my engagement with BOS, as I was unsure of where to draw the line between fully contributing my expert knowledge as an air quality scientist, versus dominating the conversations of what and where to measure, and potentially contributing to an epistemic injustice.

To take another current example of a tension between knowledges, debates in London around the efficacy of Low Traffic Neighbourhoods (LTNs), schemes that restrict through-traffic on residential streets, have, in some cases, pitted academic and community knowledges against each other. Some community groups claim that LTNs are an injustice, as they simply move traffic on to boundary roads, which already have poorer air quality than in LTNs, and home more people from a lower socioeconomic status background. Whereas, some academic research has said that LTNs work as they are leading to measurable reductions in motor vehicles and air pollution in the LTNs, with little average change in traffic or air pollution on LTN boundary roads (Thomas and Aldred, 2024; Yang et al., 2022). Moreover, that LTNs may help to ameliorate sites of potential injustice, as low-income households are more likely to live inside them (Aldred et al., 2021). Some community groups dispute these results claiming that they can see the increase in traffic with their own eyes. This perfectly encapsulates the tension of whose knowledge is superior in this situation with regards to claims of EJ, and with what consequences?

Identifying EJ is one thing, but working towards improving future EJ is another. It is unrealistic to claim that maximising the representation of knowledges alone will necessarily lead to better air quality, or a fairer share of air pollution. EJ is normative concept, and air quality is embroiled in every aspect of how we live our lives, where we are simultaneously the polluted and the polluter (albeit not to equal extents). Moreover, air quality is but part of the milieu of concerns for society, and its importance will diverge between different groups. Therefore, perhaps it is not sensible to conceive of a universal local method that will achieve diverse forms of EJ. Instead, doing EJ might mean a more skilful and careful negotiation between different lay and expert knowledges, and priorities for air quality’s importance.

7.4. Recommendations for future research

In this thesis I have been interested in the air’s material, social, cultural, economic, and political relations to understand how knowledge of it is – and should be –

produced. While I have shown how knowledge of the air is produced and represented in different contexts, and its impacts, there are some clear avenues for future research.

First, while one of the main contributions of this thesis was the development of the CAQS framework, none of the research in this thesis did an idealised version of CAQS: this was both for pragmatic reasons, and as previously said because of the revelatory nature of this PhD. That is, my PhD changed direction during the process of doing air quality science. This was undoubtedly an unavoidable limitation of the work presented in this thesis. However, it must be said that this messiness was necessary to bring to light some of the findings of this PhD. Nonetheless, further work doing CAQS from the ground up across different types of science would be valuable, both to understand how feasible it is, and what new tensions emerge. Alongside this, it would be valuable to co-develop CAQS's practice by working more closely with the range of disciplines that are engaging with and doing different forms of air quality science. Indeed, my attendance at recent air quality events has hammered home the staggering number of disciplines that are involved in different forms of air quality research, including atmospheric chemistry, psychology, medical sciences, sociology, public policy, data science, electronic engineering, criminology, and others. While in this thesis I made no claims of generalisability, as in the positivist sense, I do speak of the epistemic culture within air quality science, albeit from a partial perspective. As such, working with these different disciplines to understand where CAQS (and its modes/tenets of research) is more or less useful would be valuable. This includes working with those that are less familiar – and dare I say receptive – to some of the modes of thinking that I incorporate in CAQS, to understand how it can be meaningfully used, even if it is initially in more of an incremental way.

Second, while there have been some contributions (including my own contributions in this thesis), more work is needed to characterise and act on sociomaterial relations indoors. Biehler and Simon (2010) and Graham (2015) provide some good recommendations of potential avenues of research (which should still be further explored). However, there are some further avenues of research to pursue. First, indoor environments are a rapidly changing space with more change in the last few years than in the previous few decades: a range of new technologies (including filters, and air quality monitors) are being *differently* enrolled into indoor environments, businesses are developing new testing methodologies and voluntary guidance benchmarks, and regulations have changed including new ones being introduced and old ones being updated. Future research should track these changes as they shape human and non-human relations indoors. Alongside this, while the built environment is important, there are other indoor environments that are currently understudied and could do with a hybrid lens. This includes indoor exposures across different modes of transport which have some of the highest concentrations of certain air pollutants (Buonanno et al., 2014). Moreover, with forecasted increases in both traffic and vehicle numbers and vehicle miles driven (AQEG, 2022), it will be important to know what sociomaterial effects are incurred (and by whom), and what relations are being legitimised.

Third, in this thesis I have been interested in how air quality science produces knowledge, and how it might do so in a more environmentally just way. Through suggesting CAQS, I provided a framework for other air quality scientists to use to do this. However, the evidence produced through science is but one of part of the policy making nexus, and more better air quality science does not necessarily lead to better policies (or indeed better air quality). As such, it would be valuable for more research into how alternative modes of air quality science (such as CAQS) might both fit into existing forms of air governance (and the different levels of government that they occupy, e.g. local, national, and international), but also how new forms of air governance and CAQS can be co-developed. For example, more work investigating how a locally situated air quality science could work closely with local and regional stakeholders to develop 'place-based' approaches that deal with the air's sociomaterial (re)production.

7.5. Concluding remarks

I started this thesis with a quote by Cupples (2009) that outlined the air as a hybrid phenomenon that transcends nature/culture divides, and therefore, requires different ways of relating to the air. This way of thinking is more necessary than ever. Since I started my PhD back in 2016, IAQ has become a significant matter of concern in the UK, undoubtedly catalysed by the emergence of COVID-19. A number of new high profile reports have highlighted IAQ's importance (e.g. AQEG, 2022; Whitty and

Jenkins, 2022), and significant research funding has been committed (e.g. UKRI, 2022). Moreover, the matters of fact provided by science have been met with other public IAQ crises in a strikingly similar fashion to the case of Ella Adoo-Kissi-Debrah, who I mentioned in the Introduction chapter died following repeat asthma attacks that correlated with outdoor air pollution episodes. The tragic death of Awaab Ishak, a two-year old child who died from a respiratory condition caused by exposure to mould in his social housing association home (McCann and Horsburgh, 2022), catapulted IAQ into a matter of concern. Awaab Ishak has become the canary in the coalmine for indoor air pollution, just as Ella Adoo-Kissi-Debrah was for outdoor air pollution.

It is clear that great change is happening across the indoor/outdoor air quality interface, and air quality science will play a big role in how that change happens. This represents a significant responsibility for air quality science, and as such, a great opportunity to reassemble air quality science to embed hybrid ways of thinking. By highlighting the mediating role of air quality science in the production of the air, I hope that my thesis can lead to further development in our sociomaterial understandings of the air. Moreover, through using my critical air quality science framework, I hope that air quality scientists can better understand (and act upon) the environmental justice implications of their own practices.

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