Report into an Air Pollution Episode

Sulphur Dioxide, September 2nd 1998, Midlands and South Yorkshire

ENVIRONMENT AGENCY

Contents

A CD-ROM is included that contains much of the underlying data and animations of the NAME modelling. See the readme.txt file in the root directory of the CD-ROM for more deta

Foreword

Improving air quality is one of the Government's Quality of Life Indicators and it forms part of its Strategy for a Healthier Nation. The National Air Quality Strategy seeks to build on the substantial improvements in air quality achieved over the last thirty years by addressing a wide range of different factors, ranging from traffic control measures to the reduction of industrial emissions.

The Environment Agency, as regulator of most of the large industrial sources of air pollution, has an important part to play in this process. Also, as a body responsible for monitoring and reporting on the state of the environment at a regional scale, it is well qualified to look at air quality in a regional context. An aspect of this is to investigate major air quality episodes that, in the Midlands, are currently detected once per year on average. One such episode was in September 1998 when levels of sulphur dioxide exceeded Government guidelines across the Midlands and South Yorkshire under very unusual weather conditions.

This report documents the eighteen-month investigation of this episode carried out by the Midlands Region of the Environment Agency using innovative techniques and specialist staff. The Agency is uniquely placed as a national body to investigate incidents of this scale with the resources and expertise at its disposal. However, I wish to recognise that the detailed analysis would not have been possible without considerable help provided by the UK Meteorological Office.

The conclusions demonstrate how emissions of sulphur dioxide from a range of large industrial processes regulated by the Agency can in particular weather conditions cause such widespread impacts and public complaint.

Though such events are rare and will become even rarer as sulphur dioxide emissions are reduced over the next few years, I believe the report advances the science of air pollution episode investigation and provides a good example of how we can make environmental data and information accessible to all interested parties.

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ENVIRONMENT AGENCY REPORT INTO THE AIR POLLUTION EPISODE OF SEPTEMBER 2ND 1998

The vast majority of air pollution episodes in recent years within the UK have been of two main types. In the first, traffic generated pollutants are trapped close to the ground in stagnant winter conditions, leading to high urban concentrations of nitrogen oxides, carbon monoxide and particulate matter. The severe London episode of December 1991 was a classic case of this type. The second type of episode is a phenomenon in which ozone, nitrogen dioxide and particles are produced in increased amounts through atmospheric photochemical reactions and build up in summer anticyclonic conditions particularly in association with air masses reaching the UK from mainland Europe. Occasionally, however, episodes of exceptional pollution levels occur which are not associated with either of these patterns. Typically, concentrations of sulphur dioxide, nitrogen oxides and particulate matter have become elevated in a way which is not associated with local ground level sources. The event of September 2nd, 1998 which affected the Midlands and South Yorkshire was of this kind and has merited a very intensive investigation by the Environment Agency, who have responsibility for regulating the major industrial sources which contribute the majority of UK sulphur dioxide emissions. In this report the Agency describes the application of a state-of-the-art atmospheric numerical model to predicting ground-level pollutant concentrations arising from emissions from these major industrial sources, as a function of time. They have engaged the Meteorological Office to apply a highly sophisticated model which simulates the behaviour of the atmosphere in three dimensions over substantial time periods and which is able most impressively to predict the air pollutant concentrations observed. For the first time in the UK this has therefore allowed an attribution of measured ground-level concentrations to emissions from specific power stations and other industrial sources at large upwind distances. It therefore represents a very significant advance in our capability to understand and predict air pollution phenomena and will assist the Agency greatly in the long term in their regulatory tasks. In this particular episode, concentrations of sulphur dioxide far exceeded health based guidelines, underlining the importance of creating a full understanding, and responding in the longer term with appropriate control measures.

I enjoyed reading this report, which I believe has been put together in an exceptionally clear and logical manner, and commend it highly to those wishing to gain a fuller insight into the mechanisms by which a major air pollution episode develops.

Roy M Harrison
Professor of Environmental Health

1 Executive summary

Summary

This report by the Environment Agency details an air pollution episode that occurred across the Midlands and South Yorkshire on September 2nd 1998. This is the term used to describe a period of poor air quality, sometimes lasting for several days and often extending over a large geographical area. Although this particular episode was small in comparison with the smogs of the 1950's, it occurred across a widespread area of the Midlands and South Yorkshire and generated significant public and media interest. Due to the nature of this episode, the Air Pollution Analysis Protocol used by the Agency prompted its investigation, at the highest level (Stage III) and the initial results are published in this report.

One of the most important findings of the investigation was that the air quality standard for sulphur dioxide was exceeded across a widespread area of the Midlands and South Yorkshire on September 2nd 1998, the effect of which is likely to have caused harm[1] to some members of the public. The Agency has investigated the episode, but the quantification of the harm caused is normally beyond the capability of the Environment Agency alone. Within the full report, information taken from the Committee on the Medical Effects of Air Pollution (COMEAP) report, the World Health Organisation (WHO) and the Government's Expert Panel on Air Quality Standards (EPAQS) indicates the potential health effects of this type of air pollution episode.

This summary is intended to provide an informed overview of the main points from the investigation. For more detailed results and analysis please consult the full report and Annexes published by the Environment Agency.

Weather-driven air pollution episodes

One of the least common causes of a detected air pollution episode, is one where an industrial process, or processes, may be responsible. It is this type of episode that is believed to have occurred on September 2nd 1998.

Industrial processes release waste gases into the atmosphere through chimneys with a height normally sufficient to disperse the pollutants. Under certain weather conditions however, the pollutants can fail to disperse and so they accumulate, trapped in the local atmosphere and producing high ground-level concentrations that exceed air quality standards. Meteorological data supplied to the Agency by the Met. Office indicates that suitable weather conditions existed during September 1st and 2nd to cause an air pollution episode of this type. By linking the meteorology, with the pattern of public complaint and results from air quality monitoring stations, the following sequence of events was established:

[1] Environmental Protection Act 1990 defines 'Harm' as harm to the health of living organisms or other interference with ecological systems of which they form a part and, in the case of man, includes offence caused to any of his senses or harm to his property; and 'harmless' has a corresponding meaning.

1. September 1st 1998 - A cold weather front moved across the British Isles and stopped moving when it was over the North Sea due to high pressure over Scandinavia;

2. September 2nd 1998 am - Wind speed dropped and became light and variable for a period, allowing pollutants released to accumulate in the atmosphere without dispersion;

3. September 2nd 1998 pm - Pressure fell over the Bay of Biscay, causing light winds across Britain from the north-east. The accumulated pollution was then transported by these light winds towards the south-west;

4. September 2nd 1998 pm - A number of calls were received by the Environment Agency, Local Authorities and the emergency services, from members of the public concerned about localised 'smog' and air pollution. These calls were logged over a period of time and emerged as a clearly identified 'response-belt' running geographically from Nottingham across to Derbyshire, Staffordshire and to the Birmingham area. This 'response-belt' closely tracked the south-westward movement of the pollutant cloud.

5. September 2nd 1998 - The air quality monitoring station in Nottingham Centre, recorded a peak concentration of sulphur dioxide for this date, six and a half times the air quality standard. Other monitoring stations also recorded 'high' and 'very high' concentrations of sulphur dioxide on this date. The timing of the peaks coinciding with the south-westerly movement of the pollutant cloud.

6. September 3rd 1998 - Due to the nature of the air pollution and strength of public response the Agency commenced an investigation into the episode at Stage III, in compliance with Agency Air Pollution Episode Analysis Protocol.

Use of modelling

Because the Department for the Environment, Transport and Regions (DETR) air quality monitoring station network is limited, it cannot always track individual air pollution episodes and supply detailed information about them for analysis. The record of complaints and the results from sulphur dioxide monitoring stations indicate the progress of this air pollution episode across the Midlands and South Yorkshire. However, these fail to identify the sources of the pollution or confirm the atmospheric mechanism that caused the episode.

Numerical modelling of the emissions from the likely sources, i.e. those roughly upwind, was carried out to gain some insight into the dispersion process, help determine source culpability and to predict the likely concentrations in areas where no monitoring stations were actually located. This was carried out using the Nuclear Accident ModEl (NAME), an atmospheric dispersion model developed by the Met. Office.

Outcome

From the results of its investigation, the Agency was able to conclude the following:

- On September 1st 1998, suitable weather conditions existed to cause the development of an air pollution episode and govern its subsequent movement across a widespread area of the Midlands, during September 2nd 1998. During this episode, there were many complaints by the public and monitoring stations across the Midlands and South Yorkshire recorded concentrations of sulphur dioxide exceeding air quality standards, which means that some harm to the public is likely have occurred in these areas;
- The Environment Agency was prepared for this type of incident and responded appropriately. For example, a permanently manned emergency incident hot line to the Regional Control Centre (RCC) exists for the public and the emergency services to report pollution incidents. In addition, the Agency operates a consistent Air Pollution Episode Analysis Protocol that is used across all the regions to determine what level of response action is required to any individual air pollution episode. The Agency determined that an air pollution episode was underway across a widespread region but as no single Agency regulated process could be identified as the cause, no immediate action by the Agency was possible.

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Analysis

The Agency has identified a number of points to consider arising from the investigation and the use of NAME:

- The investigation focused upon one pollutant - sulphur dioxide. The roles of other pollutants, in particular nitrogen dioxide and nitric oxide are likely to have played a part;
- Factual knowledge about this episode is limited as air pollution monitoring stations tend to be located in major cities or towns, with relatively large distances between individual stations, or clusters of stations. The highest concentration measured was at Nottingham, and therefore analysis has necessarily focused on this monitoring station site;
- The mathematics used by the NAME model to predict how a plume initially rises from a stack is currently under revision by the Met. Office. The model should be re-run when this development is completed. In addition, the predicted peak at Nottingham is low compared with what was actually measured, but is within a factor of two. This error could be due to a number of reasons. The Agency currently considers that the under-prediction is a limitation of the meteorology used by the NAME model.

The Agency proposes to continue the investigation to overcome the identified weaknesses wherever possible.

Actions in place

The investigation presents a number of issues that should be considered for future action:

- The Environment Agency has an active programme for the control of air pollution, with specific reference to sulphur dioxide from nineteen coal and oil fired power stations in England and Wales.
- On the date in question, over 95% of the sulphur dioxide detected at monitoring stations at Birmingham Centre, Ladybower, Nottingham

Centre and Stoke-on-Trent is predicted to have originated from coal-fired power stations. Significantly however, none of the individual processes studied was in breach of authorised operating conditions, prior to, or during, this air pollution episode. Also air quality objectives were not breached at the DETR monitoring station in the Agency's Midlands Region during the 1998 calendar year. In the light of developments to the Government's new energy policy[2], the Agency has placed new controls on individual power stations and with these in place, it is expected that power station emissions of sulphur dioxide will reduce by approximately 60% by 2005. It is anticipated that the package of controls will achieve the objectives of the Government's National Air Quality Strategy (NAQS), in relation to sulphur dioxide, and will help to reduce the frequency and intensity of air pollution episodes such as this one.

- A flue gas desulphurisation (FGD) plant fitted to the power station can remove approximately 90% of the sulphur dioxide in the flue gas. Although FGD can be added to existing power stations, significantly improving their environmental performance, the cost of doing this can run into several hundred million pounds depending on the size and design of the generating plant. Because the technology is expensive to install and also increases the running costs of the station, it is only cost-effective to install it where the station has a long expected lifetime and/or is operating at high levels of utilisation. In line with Government policy, the Agency will be seeking to ensure that each major generating company fits FGD on at least one of its stations.

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[2] Conclusions of the review of energy sources for power generation and Government response to the 4th and 5th reports of the Trade and Industry Committee. Cm 4071 October 1998.

2 Introduction & overview

Summary

This report by the Environment Agency helps to improve our understanding of air pollution episodes and this section provides background information on the role of the Agency and the monitoring and measuring of air quality in the UK.

- **The role of the Environment Agency**
  The Environment Agency has a duty to ensure that any industrial processes it regulates subject to Integrated Pollution Control (IPC) use the Best Available Techniques Not Entailing Excessive Costs (BATNEEC) to prevent or, where this is practicable, minimise and render harmless, polluting emissions.
- **Air quality standards and objectives**
  Air quality standards are benchmarks set by health experts on behalf of the Government to identify concentrations of airborne pollutants that should not result in harm to public health. Air quality objectives are then set by Government taking into account the feasibility of achieving the air quality standards.
- **Air pollution monitoring**
  Air pollution is monitored to ensure that these air quality objectives are achieved.
- **Air pollution sources**
  Pollution is emitted into the air from many sources such as industrial processes, transport and urban areas. In addition, there are natural processes that emit the same pollutants into the atmosphere.
- **Air pollution episodes**
  An air pollution episode is the term used for a period of poor air quality, sometimes lasting for several days and often extending over a large geographical area.

What is the role of the Environment Agency?

The Agency has broad responsibilities to protect the environment in England and Wales. In summary, these include:

- Protecting surface and ground water quality;
- Control of water abstraction;
- Main river flood defence;
- Regulation of waste treatment and disposal;
- Regulation of major polluting industries;
- Regulating the keeping and use of radioactive substances;
- Regulating the accumulation and disposal of radioactive waste;
- A role in conservation, recreation, education and sustainable development.

These are undertaken in liaison with other environmental regulators including Local Authorities (LAs), who also have their own broad responsibilities to protect the public and specific duties towards protecting the atmospheric environment.

The support service provided by the Agency to fulfil its responsibilities includes maintaining a free call emergency telephone hot-line available to the public for reporting incidents; offering practical advice where applicable and issuing flood alerts when appropriate. A specialist team of experts is on-hand to advise on the best course of action in the event of an emergency, and to provide a rapid response to any potentially harmful event. This service is operable 24-hours a day, 7-days a week, 365 days a year.

The Agency works closely with Local Authorities and the full range of emergency services to endeavour to ensure that appropriate measures are taken to mitigate potentially harmful environmental events, including air pollution episodes.

What is the Environment Agency's regulatory responsibility?

The Environment Agency has a duty to ensure that any industrial processes it regulates subject to IPC use BATNEEC to prevent or, where this is not practicable, minimise and render harmless, polluting emissions.

In fulfilling this responsibility and carrying out these duties the Agency does not:

- Investigate the health risks from atmospheric pollutants - this is the remit of the Department of Health;
- Set health standards, air quality standards or air quality objectives;
- Assess the health impact of the processes it regulates; this is the remit of local Health Authorities and the Department of Health.

Within its function however, the Agency does:

- Have a statutory responsibility to prevent or, where this is not practicable, minimise and render harmless, emissions from processes subject to Integrated Pollution Control (IPC) under the requirements of the Environmental Protection Act 1990 (EPA90);
- Need to have a view on the health impact of the processes it regulates;
- Set authorisation conditions for individual processes consistent with Best Available Techniques Not Entailing Excessive Cost (BATNEEC);
- Endeavour to ensure that there are no breaches of EU AQ Daughter Directive Limit Values when setting these authorisation conditions for releases to air;
- Have regard to the requirements of the National Air Quality Strategy (NAQS) in discharging its pollution control functions under The Environment Act 1995 (EA95);
- Undertake Pollution Prevention and Control (PPC) - from mid-2000 the EU Integrated Pollution Prevention and Control Directive (IPPC) will progressively replace IPC by PPC. Under PPC, integrated permitting will be applied to more processes than are currently regulated under IPC. Regulators will be required to consider a wider range of environmental impacts (including energy efficiency, noise and site restoration) in setting authorisation conditions. These conditions will require the process to apply the Best Available Techniques (BAT), based on an assessment of costs and benefits, to minimise pollution. BAT for PPC processes is therefore not dissimilar to BATNEEC for those regulated by IPC.

All of the processes identified as potential sources for this episode are subject to IPC regulation by the Agency and were examined as part of this investigation.

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What are air quality standards and air quality objectives?

Air quality standards are benchmarks set by the Government to identify concentrations of airborne pollutants that should not result in harm to public health or the environment. The air concentration of pollutants are monitored to measure compliance with these air quality standards.

Air quality standards are set purely with regard to scientific and medical evidence on the effects of a particular pollutant on man or the environment. The purpose of setting air quality standards is to establish a common measure against which it can be shown that polluting emissions have been rendered harmless. Air quality standards are however, based solely on health guidelines and do not take into account the practical implications or the cost involved of achieving 100% compliance. For example, on occasions, the air quality standards may be exceeded for social and cultural reasons (e.g. Guy Fawkes Night) or it may be that

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achieving 100% compliance may require disproportionately expensive abatement measures. For this reason, the Government sets air quality objectives which may allow the air quality standard to be exceeded for a set number of occasions in a calendar year.

Air quality objectives are more flexible and allow other issues to be taken into consideration, such as: economic efficiency, practicability, technical feasibility and timescale.

During the air pollution episode on September 2nd 1998 the 15-minute air quality standard for sulphur dioxide was exceeded across a widespread area. However, even including the measurements for this particular episode, the air quality objectives (to be achieved by 31 December 2004) were not breached at any monitoring site in the Midlands during the 1998 calendar year.

What are the main sources of air pollution?

Pollution is emitted into the air from many sources such as industrial processes, transport and urban areas. In addition, there are natural processes that emit the same pollutants into the atmosphere. Almost 90% of the UK's sulphur dioxide emission is from processes regulated by the Environment Agency - there are few natural sources of sulphur dioxide in the UK. Approximately two thirds of the sulphur dioxide emitted in the UK is from oil and coal fired power stations. Processes such as oil refineries generate a large proportion of the remainder, together with cement works, iron and steel works and other installations with large heating systems.

Who monitors air pollution?

The Environment Agency carries out some monitoring of the processes that it regulates, and their impact on the atmospheric environment, but in general, air pollution levels are mainly monitored by the DETR and LAs.

Some individual Government organisations monitor specific air pollution issues; for example, the Highways Agency monitors pollution levels near major road and motorway networks and some individual industrial companies monitor air pollution near their installations. This monitoring is often carried out prior to any major operational changes at the site, or to demonstrate compliance with air quality objectives, and enables the company to ensure that these changes do not impact on the environment to unacceptable levels. This type of industrially measured air pollution data was not obtained for use in this report in order to remain independent.

Why is air pollution monitored?

Air quality monitoring provides raw measurements of air pollutant concentrations. With appropriate analysis and interpretation, these measurements can be transformed into useful information on the quality of the air. One of the ways air pollution is assessed is by placing pollutant concentration into status bands such as 'high' and 'very high' against the recognised air quality standards.

Air pollution monitoring has many other uses, the principal ones are for research, information to the public, to assist the Government in setting policy and demonstrating compliance with legally set pollution limits.

What pollutants are measured?

A number of DETR and LA networks contribute information in order to build up a comprehensive picture of air quality throughout the UK. A variety of methods are used to measure specific pollutants. The pollutants monitored include ozone, oxides of nitrogen, sulphur dioxide, carbon monoxide, a range of hydrocarbons, particulates and lead. However, not all monitoring stations monitor all of these pollutants.

What is an air pollution episode?

An air pollution episode is the term used for a period of poor air quality, sometimes lasting for several days, often extending over a large geographical area. During an air pollution episode, concentrations of all the measured pollutant substances may be increased, or only one may be affected.

They are caused in different ways:

- During winter months, cold, stable weather conditions can form an atmospheric layer that traps pollutants close to their sources and prevents their dispersion. As a result, elevated concentrations of a range of pollutants can build up over several days. In the 1950's and 60's the biggest source of pollution was domestic coal burning, producing large amounts of black smoke and sulphur dioxide. More recently, however, the major pollutant source in the UK is the motor vehicle. High concentrations of nitrogen oxides, particulates and hydrocarbons are experienced in particular during cold foggy periods in winter. These conditions don't only occur in the winter;
- During the summer, a completely different type of episode occurs during hot and sunny weather. Pollutants emitted within the UK, or from other parts of Europe, can be transported long distances, reacting with each other in sunlight to produce high levels of ozone, and other photochemical pollutants.

These are the most common causes of detected air pollution episodes.

- A considerably rarer cause of detected air pollution episodes, is one where an industrial process (or processes) may be responsible. It is this type of episode that is believed to have occurred on September 2nd 1998.

Industrial processes release waste gases into the atmosphere through chimneys with a height normally sufficient to disperse the pollutants. Under certain weather conditions however, the pollutants can fail to disperse and so they accumulate, trapped in the local atmosphere and producing high ground level concentrations that exceed the air quality standards. For air pollution episodes of this type, monitoring stations that record hourly or every 15 minutes provide the most significant information and the clearest picture of activity.

Please refer to Annex I for more information on air pollution episodes and refer to Annex II for further information on the Air Pollution Episode Analysis Protocol used by the Agency.

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3 Air pollution episode – September 2nd 1998

Summary

This section looks at the events leading up to and during, the air pollution episode on September 2nd 1998. It examines the pattern of public complaint that the Agency received and how the Agency responded during and after the episode on September 2nd 1998. It explains why the Agency decided to undertake an investigation into this episode and outlines the air quality monitoring results and meteorology information that was subsequently obtained.

It shows why the investigation has been limited to sulphur dioxide and how the geographical study area was chosen.

How did the Agency become aware that an air pollution episode was occurring?

The Environment Agency maintains a permanently manned emergency incident hotline at its Regional Control Centres (RCC) for members of the public to use to report pollution incidents. For any such incident, the Environment Agency can inform the wider public, other agencies and organisations and take appropriate action or intervene to protect the environment.

On September 2nd 1998 a number of calls were received by the Environment Agency, Local Authorities and the emergency services, from members of the public reporting localised 'smog', and 'chemical smells'. These calls were logged and emerged as a clearly identified 'response-belt' running geographically from Nottingham across to Derbyshire, Staffordshire and the Birmingham conurbation.

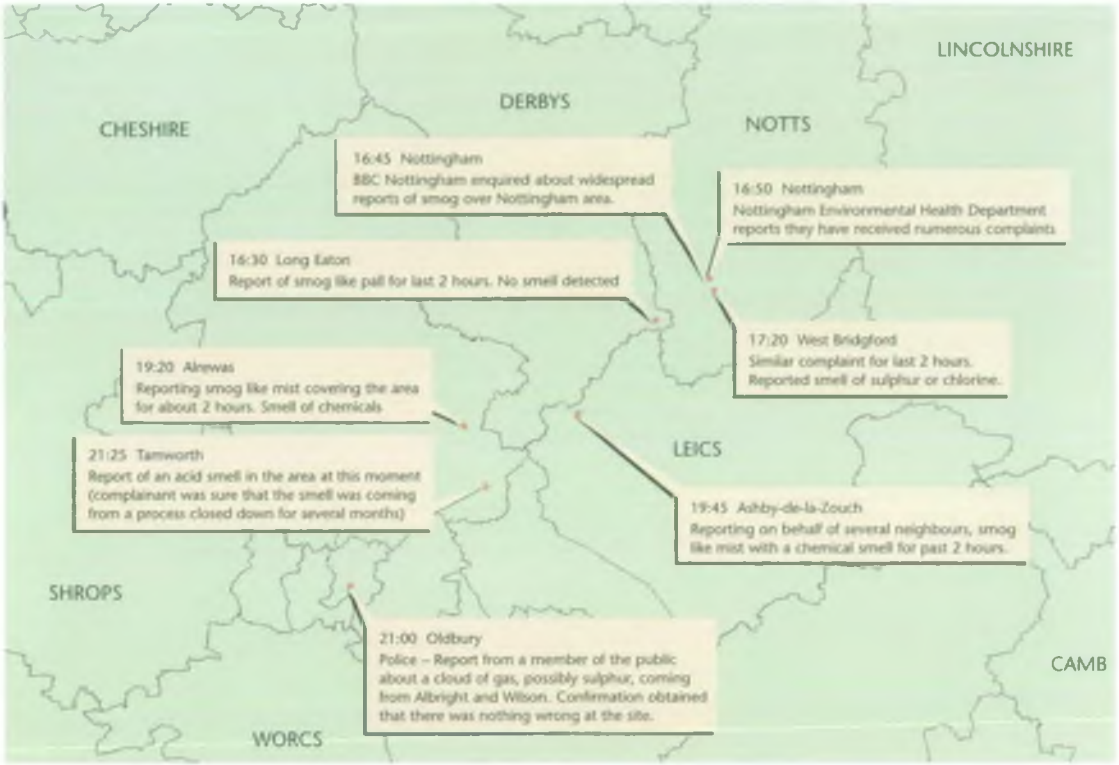
The RCC also dealt with enquiries from the media and liaised with Local Authorities and emergency services. It was quickly determined by the Agency that an air pollution episode was underway across a widespread region but no single Agency regulated process was identified as a possible cause and therefore no immediate action by the Agency was possible.

Midlands RCC - Some Facts and Figures

- Handles 240,000 calls a year;
- 8000 incident reports from emergency services, public and media annually;
- Monitors operational alarms such as river level, rainfall, intruder, and fire;
- The 0800 incident hotline number terminates in the RCC;
- Monitors lone workers outside office hours, carries out identity checks for bailiffs, retains a list of sites, monitors CCTV systems;
- Has been running for 10 years - manned continually with the exception of systematic fire drills;
- Has 5 shift operators, 3 part time operators.

What complaints were received by the Agency?

Figure 3.1 Summary of Midlands' Regional Control Centre log for September 2nd 1998



It can be seen from Figure 3.1, that the complaints received originated in the Nottingham area and then came from various locations to the south and west of this area. Reference is made throughout, to the smell of 'chemicals' or sulphur with a commonly estimated duration time of about 2 hours. Media interest was generated in the Nottingham area only.

What was the Agency response to these complaints?

The Agency operates a consistent Air Pollution Episode Analysis Protocol which is used across all the Regions to determine what level of response action is required to any individual episode. It has three levels of analysis, with clear criteria for each level and the highest being Stage III. As a matter of procedure, staff at the RCC relayed all the information received to the regional duty officer and duty manager and all available details were provided to the Local Authorities in the areas concerned. Regional air quality experts were also informed and consulted.

The structure of the Protocol allowed the Agency to determine that analysis at the highest level was required, due to the nature of the episode and its potentially harmful effects. This investigation commenced on September 3rd 1998. See Annex II for more information on the Protocol.

What was the initial focus of the investigation?

Whilst the pattern of public complaint indicated that the air pollution episode was widespread across East and West Midlands, complaints were most severe and numerous in Nottingham City and the surrounding area. The initial focus for the investigation was therefore on the monitoring data from the DETR monitoring stations in the centre of Nottingham and the Birmingham area, although measurements from other stations were also considered at a later stage.

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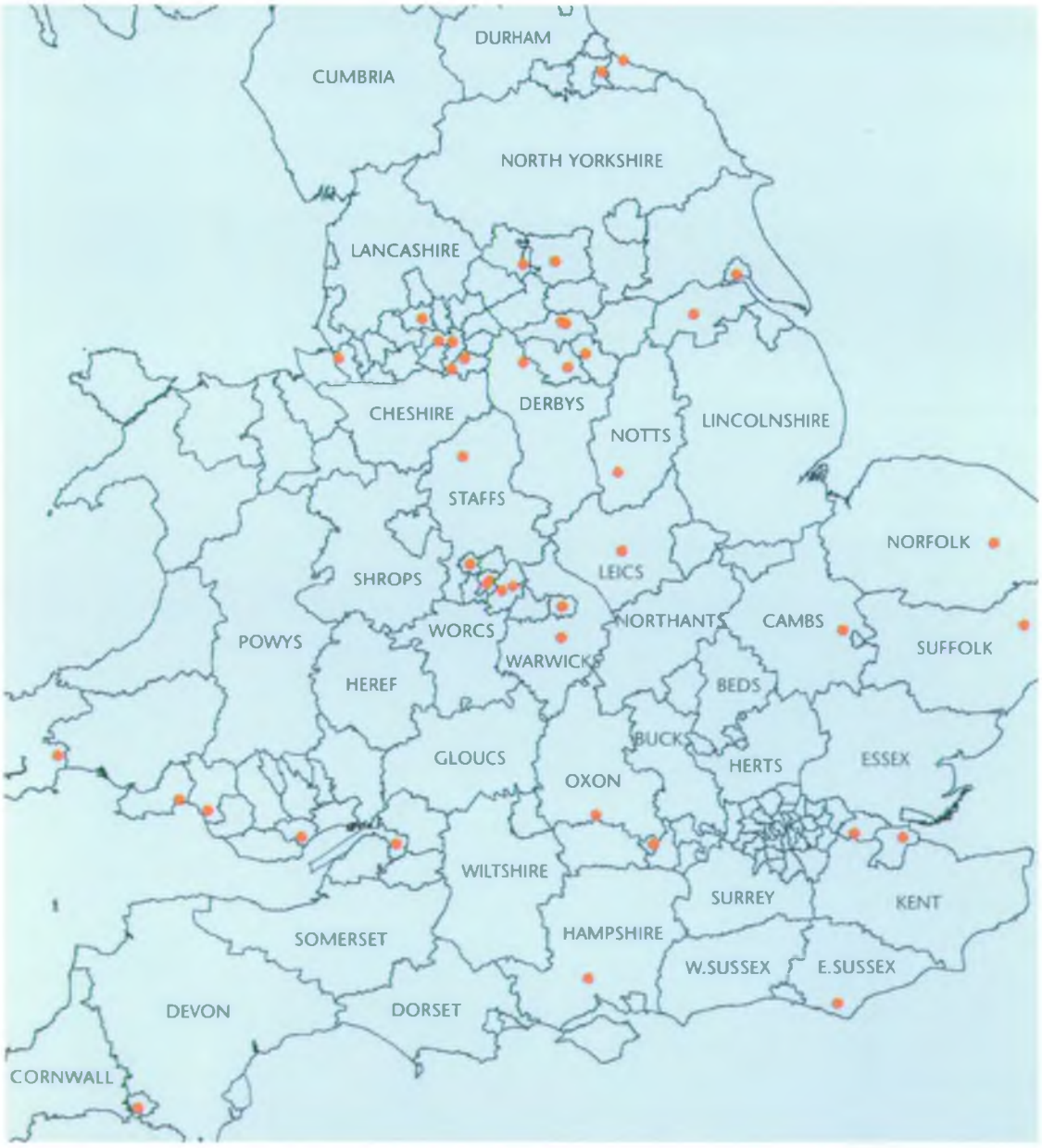
Where was air pollution monitored?

The DETR funds a network of air pollution monitoring stations in the UK which is managed by Stanger Science and Environment and the National Environment Technology Centre (NETCEN). In the event of an air pollution episode being recorded at a DETR monitoring station, NETCEN is contractually bound to provide the relevant monitoring station data. The Met. Office is also bound to provide information on the indicative weather conditions. Many of these DETR stations recorded the passage of this air pollution across the Midlands. Data for the air pollution episode on September 2nd 1998 from both these sources was automatically faxed to the Agency.

Figure 3.2 shows the location of the DETR monitoring stations that measure sulphur dioxide and return 15 minute mean results. The Environment Agency operates mobile air pollution monitoring equipment, but on September 2nd 1998, none was operating directly in the path of the pollution.

Figure 3.2 DETR sulphur dioxide monitoring stations (excluding London)



What measurements were recorded at Nottingham for September 2nd 1998?

The Nottingham monitoring station measures carbon monoxide, ozone and particulates (PM_{10}) as 1 hourly means; and nitric oxide, nitrogen dioxide (which can be added together to give oxides of nitrogen) and sulphur dioxide as 15 minute means. Figures 3.3 to 3.5 show the measurements of nitrogen dioxide, particulates and sulphur dioxide respectively, recorded at Nottingham during the period 1st to 3rd September 1998. These show peaks occurring at times corresponding to the timings of calls from the public logged at the RCC.

Figure 3.3 DETR Nottingham Centre: nitrogen dioxide concentration 1st to 3rd September 1998

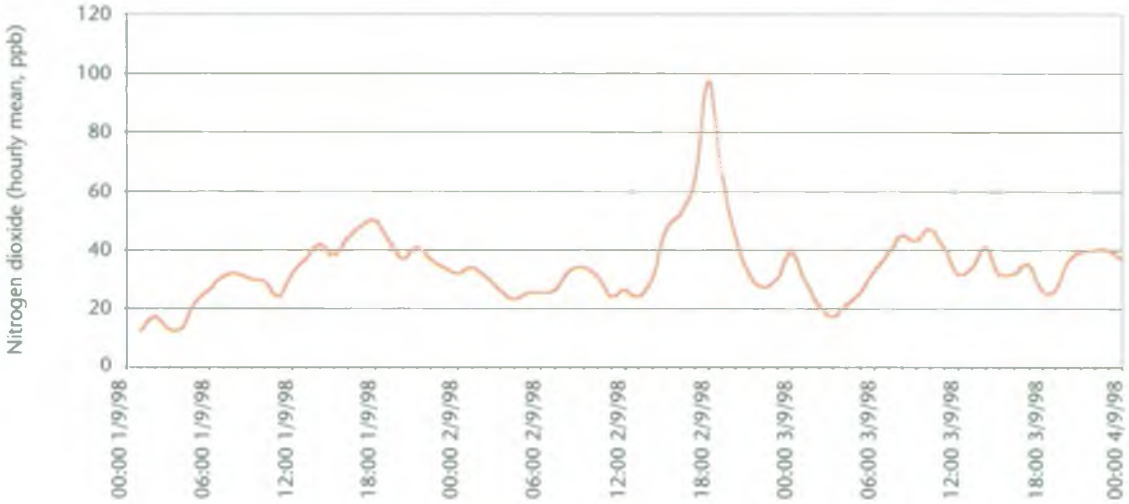


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Figure 3.4 DETR Nottingham Centre: particulates concentration 1st to 3rd September 1998

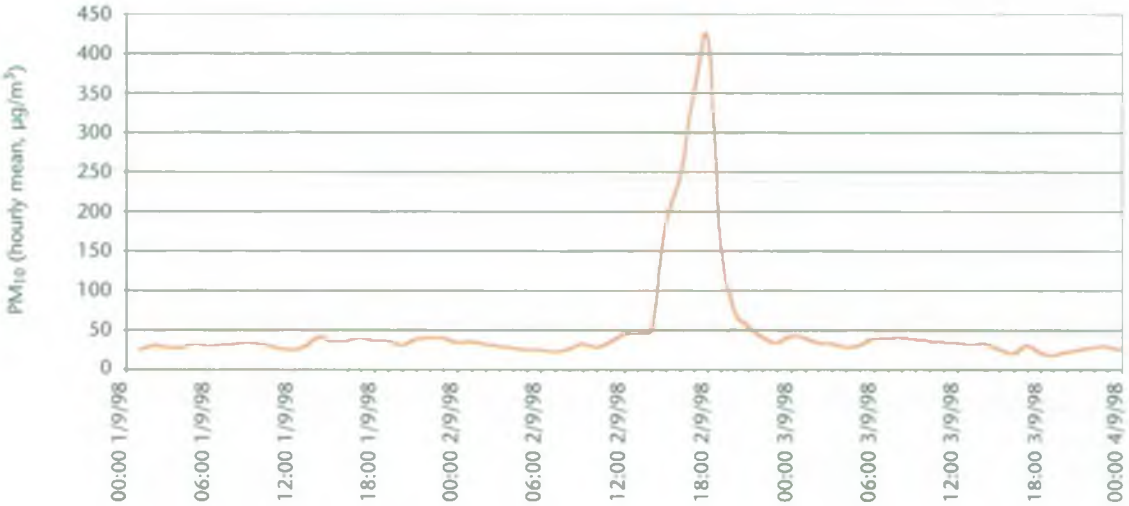

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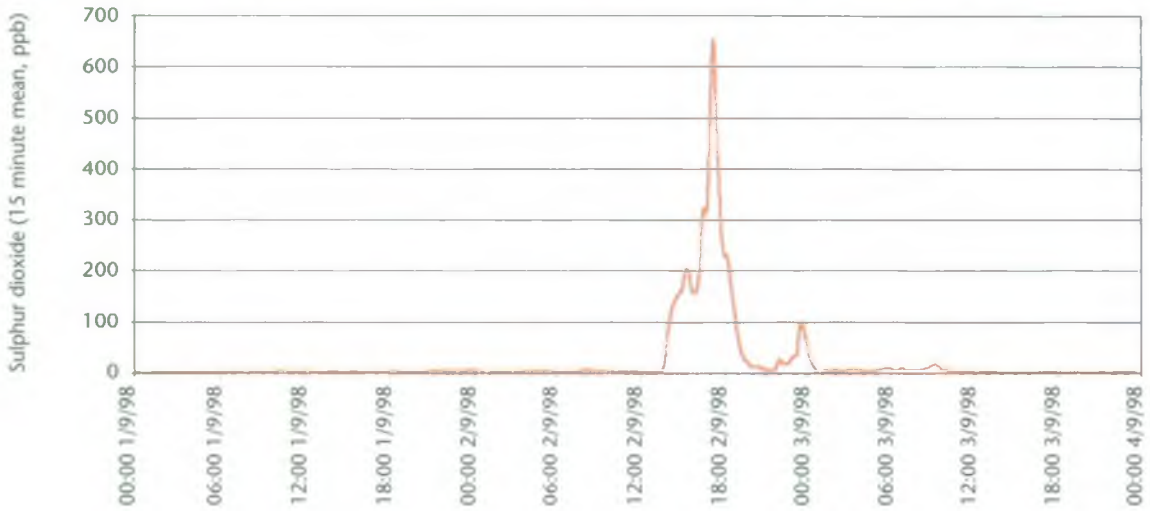
Figure 3.5 DETR Nottingham Centre: sulphur dioxide concentration 1st to 3rd September 1998



Why is sulphur dioxide of particular importance?

The sulphur dioxide peak is of particular importance as this pollutant is emitted by many large industrial sites regulated by the Environment Agency. These sites can also emit particulates and oxides of nitrogen, but due to the scale of the episode, some simplification is required; therefore sulphur dioxide alone is the subject of this report. The Agency is aware however, that the levels of particulates and oxides of nitrogen are partially attributable to many other sources including smaller processes and vehicular emissions. The Environment Agency will therefore undertake a closer examination of the role of these and of carbon monoxide in this episode as a future action.

What sulphur dioxide measurements were recorded?

Based on the geographical pattern exhibited by the record of public response and the direction of travel believed to have been taken by the air pollution, an initial study area extending from Kidderminster in the south-west to Middlesbrough in the north-east was selected.

Sulphur dioxide monitoring results were obtained from stations in the DETR Network for this area and Table 3.1 shows data extracted for all these stations.

Table 3.1 Summary of sulphur dioxide monitoring station results for September 2nd 1998

STATION	PEAK CONCENTRATION (15 MINUTE MEAN, PPB)	START TIME*	PEAK TIME	FINISH TIME*
		2/9/1998 GMT		
Barnsley 12	278	10:15	16:30	20:15
Barnsley Gawber	237	10:30	15:30	20:30
Birmingham Centre	211	18:15	21:15	> 23:45
Birmingham East	178	18:00	21:15	> 23:45
Bolton		no peak		
Bradford Centre		no peak		
Bury Roadside	129	14:15	16:00	21:15
Coventry		no peak; instrument failure		
Hull Centre	91	9:45	9:45	13:00
Ladybower	105	14:30	17:30	21:30
Leamington Spa		no peak; instrument failure		
Leeds Centre		no peak		
Leicester Centre	74	13:45	16:00	18:00
Liverpool		no large peak; many small peaks during day		
Manchester South	54	16:15	18:15	20:30
Mansfield+		no peak		
Middlesbrough		no large peak; many small peaks during day		
Nottingham Centre	653	14:00	17:30	21:00
Oxford Centre		no peak		
Redcar	97	5:45	7:00	12:15
Rotherham Centre		no peak		
Sandwell Oldbury	206	18:45	20:45	>23:45
Salford Eccles	74	15:45	16:15	18:45
Scunthorpe		no peak		
Sheffield Centre	90	10:45	17:45	21:30
Stockport	79	15:45	17:45	20:15
Stoke-on-Trent Centre	74	19:15	20:00	>23:45
Sunderland		no peak		
Wolverhampton	88	19:00	20:15	>23:45

* Start and finish times are arbitrarily defined as when the concentration rose above 10 ppb and then fell back below 10 ppb respectively

\+ Note that the Mansfield data is from a monitoring site operated by the Local Authority and is not DETR affiliated.

Additionally, note that:

- Coventry and Leamington Spa monitoring stations were also not operational on September 2nd 1998 during the period of time being investigated;
- Additional figures in Annex III show the 15-minute mean sulphur dioxide concentration (ppb) at each DETR station and Mansfield DC's station within the study area for the single day of the September 2nd 1998.

Where did the sulphur dioxide peaks occur?

Sulphur dioxide peaks occurred:

- Sequentially from north-east to south-west at Barnsley, Sheffield, Ladybower and Stoke-on-Trent and successively reducing in size;
- Sequentially from north-east to south-west in Nottingham and Birmingham (including Sandwell and Wolverhampton) again reducing in size;
- Relatively small peaks were also measured in Manchester, Stockport, Eccles, and Bury, which lie outside the Agency's area of investigation but indicate how widespread the episode was;
- At an early stage, small peaks also occurred in Redcar and Hull. This pollution may then have travelled and contributed to the greater peaks recorded within the area of detailed investigation at a later stage.

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Sulphur dioxide peaks **did not** occur at:

- Mansfield - which is between Nottingham and Sheffield, suggesting that two distinct plumes occurred individually at these locations rather than one large plume covering the entire area;
- Leeds - giving a north-westerly limit to the episode area;
- Oxford - giving a south-easterly limit to the episode area.

What do these results suggest?

A link can be made between the timings of public complaints and the presence of sulphur dioxide shown by results from air quality monitoring stations across the Midlands. Table 3.2 shows this comparison. Further figures for DETR monitoring stations in the south and south west of England and South Wales show an absence of any significant sulphur dioxide peaks recorded for September 2nd or September 3rd 1998. This suggests that the pollution became diluted and dispersed before reaching these areas.

Overall, these results indicate a south-westerly movement of the pollution across South Yorkshire and the Midlands with the occurrence of two distinct trends, or plumes.

Additional monitoring results are contained within Annex III.

The monitoring results for the dates in question suggested that for the Midlands, there were two distinct plumes of air pollution brought in from a north-easterly direction. One impacted on Nottingham across to Birmingham; the other impacted on Barnsley, Ladybower and across to Stoke-on-Trent. The suggested existence of at least two separate plumes also implied the existence of at least two separate sources.

Did sulphur dioxide levels exceed the standards and objectives during this air pollution episode?

Please see Annex IV for a description of air quality standards and objectives for sulphur dioxide, for details of the banding of air quality for public information purposes and of the potential health implications.

The sulphur dioxide measurements for the air pollution episode on September 2nd 1998 can be compared with Government's sulphur dioxide standards and objectives. Table 3.3 shows this comparison, listing the exceedences of the three sulphur dioxide standards in the calendar year in total and on the day of September 2nd 1998.

Only sites where an exceedence occurred on September 2nd 1998 are shown. Table 3.4 shows the number of exceedences permitted per calendar year of the air quality standards for sulphur dioxide giving the national air quality objectives.

Table 3.2 Comparison of complaints and sulphur dioxide peaks

STATION	COMPLAINT	START TIME	PEAK TIME	FINISH TIME
		GMT		
Birmingham Centre		18:15	21:15	>23:45
Birmingham East		18:00	21:15	> 23:45
Nottingham	16:30 for past 2 hrs Nottingham area	14:00	17:30	21:00
Sandwell Oldbury	21:00 report of gas cloud from Albright and Wilson	18:45	20:45	>23:45
Wolverhampton		19:00	20:15	>23:45

Table 3.3 Exceedence of the sulphur dioxide standards for September 2nd 1998 and the 1998 calendar year

MONITORING STATION	CALENDAR YEAR 1998, NUMBER OF EXCEEDENCES OF					
	EPAQS 100 PPB 15 MINUTE MEAN		WHO 132 PPB 1 HOUR MEAN		WHO 47 PPB 24 HOUR MEAN	
	TOTAL 1998	2/9/1998	TOTAL 1998	2/9/1998	TOTAL 1998	2/9/1998
Barnsley 12	30	11	5	2	0	0
Barnsley Gawber	28	10	3	2	0	0
Birmingham East	6	5	1	1	0	0
Birmingham Centre	16	6	1	1	0	0
Ladybower	27	2	1	0	0	0
Nottingham Centre	23	19	4	4	1	1
Sandwell Oldbury	6	5	1	1	0	0
Total	109	56	15	11	1	1

Table 3.4 Permitted exceedences of sulphur dioxide per calendar year

CONCENTRATION	MEASURED AS	EXCEEDENCES PER CALENDAR YEAR
132 ppb	1 hour mean	24
47 ppb	24 hour mean	3
100 ppb	15-minute mean	35

What does the comparison show?

Comparison of permitted exceedences with the recorded number of actual exceedences shows that none of the stations recorded any breach of these objectives on September 2nd 1998 alone. However, the episode accounted for the only exceedence of the WHO 47 ppb 24 hour mean standard, 11 of the 15 exceedences of the WHO 132 ppb 1 hour mean and 56 of the 109 exceedences of the EPAQS 100 ppb 15 minute mean.

As the objectives are based on a calendar year, it was necessary for this investigation to examine the full year of data from each monitoring station to evaluate the impact of the air pollution episode in this conclusion. Thus, none of these monitoring stations showed a breach of the Air Quality Objective. Additionally, it should be noted that the deadlines for achieving the sulphur dioxide objectives are December 31st 2004 for the 1 hour and 24 hour objectives and one year later for the 15 minute objective.

How do sulphur dioxide levels during the episode compare with air quality bands?

The peak concentration at each monitoring station can be compared to the air quality band thresholds to determine what advisory status should have existed during the episode (these bands are defined in Annex IV). On September 2nd 1998, the air quality monitoring station in Nottingham, recorded a peak concentration of sulphur dioxide six and a half times the air quality standard.

Other monitoring stations also recorded 'high' and 'very high' concentrations of sulphur dioxide on this date, in locations from Barnsley in the north, to Birmingham in the south, coinciding with the south-westerly movement of the pollutant cloud.

From Tables 3.3 and 3.5, it is evident that the recorded presence of sulphur dioxide for this air pollution episode was at levels expected to be harmful to sensitive individuals.

Table 3.5 Advisory air quality status for September 2nd 1998

MONITORING STATION	PEAK CONCENTRATION PPB, 15 MINUTE MEAN	BAND
Barnsley 12	278	High
Barnsley Gawber	237	High
Birmingham Centre	211	High
Birmingham East	178	Moderate
Nottingham Centre	653	Very High
Sandwell Oldbury	206	High

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What were the potential health effects during the episode based on the COMEAP report?

The basis of the EPAQS standard and the COMEAP Quantification Reports (see Annexes IV and V) is very different. The EPAQS standard is based on effects observed in asthmatic subjects in clinical exposure trials. At the time that it was produced there were no suitable data from population based epidemiological studies to derive a standard in any other way. By the time that the COMEAP report was written, the results of the APHEA (see Annex V) study were available which provided a coefficient relating 24 hour mean sulphur dioxide concentration to mortality and morbidity outcomes. By combining this with maps of sulphur dioxide and population it was possible to calculate the effects of sulphur dioxide on mortality and hospital admissions.

Table 3.6 shows the 24 hour mean values for September 2nd 1998, for the study area showing only those monitoring stations where a value of greater than 10 ppb as a 24 hour mean was recorded. To put the recorded concentrations into context, the table also includes the minimum, maximum and median values for 1998.

Using the 24-hour mean data from within the episode it would be quite possible to calculate a health outcome using maps of sulphur dioxide concentration and population. However, whether this would be appropriate or reliable is questionable, as exposures may not well represent those experienced by urban dwellers in the APHEA study.

What anomalies occurred in the data?

The Agency examined the data for anomalies:

The arrival times recorded at the four monitoring stations in the Birmingham area are consistent with a plume travelling in a south-west direction. However, Wolverhampton, the farthest (most westerly) station recorded the earliest peak time as shown in Table 3.7.

Table 3.6 24-hour mean sulphur dioxide concentrations for September 2nd 1998

MONITORING STATION	CONCENTRATION PPB, 24 HOUR MEAN			
	1998 CALENDAR YEAR			2-9-1998
	MINIMUM	MEDIAN	MAXIMUM	
Barnsley 12	0	3	37	36
Barnsley Gawber	2	7	36	33
Birmingham Centre	0	3	45	21
Birmingham East	0	2	23	15
Nottingham Centre	1	5	60	60
Ladybower	0	1	27	15
Sandwell Oldbury	0	2	25	20
Sheffield Centre	1	4	36	22
Stoke-on-Trent Centre	0	5	30	10
Wolverhampton	0	3	39	15

Table 3.7 Arrival and peak timing in the Birmingham area

STATION (EAST TO WEST DIRECTION)	ARRIVAL TIME	PEAK TIME
	GMT	
Birmingham East	18:00	21:15
Birmingham Centre	18:15	21:15
Sandwell Oldbury	18:45	20:45
Wolverhampton	19:00	20:15

Was the Nottingham device functioning correctly?

The technology used to measure sulphur dioxide concentration at the Nottingham station is also sensitive to hydrocarbons, which means that a hydrocarbon peak could be shown as sulphur dioxide on the records. To prevent this from happening and avoid any cross-sensitivity, a device is fitted to selectively remove hydrocarbons.

Extremely high concentrations of hydrocarbons may overload this device and prevent it from functioning correctly. Under these conditions, it is possible that the presence of excessive hydrocarbons may have been recorded as a measured sulphur dioxide peak for Nottingham City centre.

The maintenance records have been examined and the device was working correctly prior to and after the episode. Records show that it removed approximately 2000 ppb of m-xylene (a hydrocarbon that the instrument is most sensitive to) with no impact on the sulphur dioxide reading. This indicates the instrument was working without fault.

Was the measured peak hydrocarbon rather than sulphur dioxide?

DETR operates a network of hydrocarbon monitoring stations. Geographically these are sparse compared with sulphur dioxide monitoring stations, the nearest to Nottingham being at Birmingham East. Figure 3.6 shows the total hydrocarbon concentration at Birmingham East recorded on the afternoon of September 2nd 1998, together with the sulphur dioxide concentration.

The figure shows no evidence of a hydrocarbon peak at Birmingham East. The modelling section of this report also indicates that the air pollution measured over Nottingham then moved directly towards Birmingham East. As there was no evidence of a hydrocarbon peak in existence at Birmingham East, then it is most likely that no substantial (i.e. > 2000 ppb) hydrocarbon peak would have existed for the air pollution at Nottingham either, and therefore could not have affected the performance of the monitoring equipment at this site.

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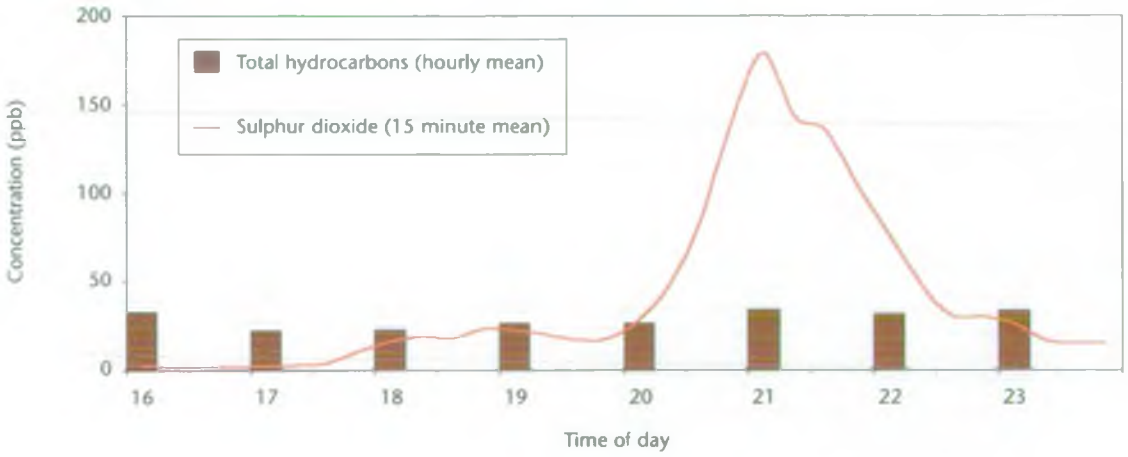
Figure 3.6 Total hydrocarbons and sulphur dioxide at Birmingham East monitoring station



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Nottingham City Centre DETR Monitoring Station

The monitoring station is within a self-contained, air-conditioned housing located in a pedestrianised area. The nearest road is located some 30m from the site and is a major through road within the city centre. Traffic flow is approximately 24250 vehicles per day. The manifold inlet is approximately 3.5m high. The surrounding area comprises retail outlets and city centre business premises in an urban pedestrian centre.

Site Address	Clinton Street East Nottingham
OS Grid Reference	SK 574 400
Site Type	Urban Centre
Start Date	2/9/96
Pollutants measured	Ozone, carbon monoxide, sulphur dioxide, nitric oxide, nitrogen dioxide, particulates

What contribution did weather conditions make to this episode?

The following panel, provided by the Met. Office describes the weather situation over the British Isles during the episode and an interpretation of the likely effect on pollutant dispersion.

Meteorological situation, 2nd September 1998.

"During 1st September an occluded cold front moved east across the British Isles and became slow moving over the North Sea due to the presence of high pressure over Scandinavia. Behind the cold front the pressure field over Britain was very slack, with light and variable winds and areas of fog over eastern parts of Britain persisting into the afternoon of 2nd September. Pressure had been falling over Biscay and a slack low drifted north pushing the trailing edge of the front back into south-east England, with outbreaks of rain reaching a line from Suffolk to the Bristol Channel by 18UTC* on 2nd. In the course of that afternoon the surface winds gradually became light NE'ly over the East Midlands. At Nottingham the upper winds were light and variable at first, with a broadly SW'ly drift above about 800m. By midday the boundary layer flow was N to NE, but the flow remained light SW above about 700m; by late afternoon the upper winds were NE up to about 1500m, but more N to NE at low level.

The general effect of these wind changes was to hold and perhaps pool emissions upwind of Nottingham, and then to bring the material SW in the course of the afternoon. The sonde ascents from Watnall showed a distinct inversion at around 970mb both at 1115 and 1715UTC, and there is little evidence to suggest that it broke down during the afternoon, or, if it did, why it should reform at about the same level. This level, about 470m+ above the city, is low for a September afternoon, although for the reasons outlined above insolation cannot have been strong that day. Thus the situation as regards boundary layer depth remains rather obscure, and this may have been a critical factor in the development of the episode; certainly the NAME model only approaches the measured sulphur dioxide concentrations if the boundary layer is kept shallow (assuming only power station sources). Estimates of boundary layer depth made assuming dry adiabatic lapse rates from the surface at the time of maximum temperature gave a deeper boundary layer and a more dilute modelled plume."

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* UTC - meteorological organisations world-wide use a consistent time system known as Universal Time Co-ordinates, for the UK, you can say that UTC = GMT, see also the Glossary.

\+ Given as height above sea-level

In summary, the following sequence of events occurred in the weather over Britain:

1. September 1st 1998; A weather front moved across the British Isles and became stationary over the North Sea due to high pressure over Scandinavia.

2. September 2nd 1998 am; Wind speed across Britain dropped and became light and variable, with several hours of zero wind speed being recorded near Nottingham. Pollution emitted by industrial sources, traffic and urban areas accumulated, unable to disperse.

3. September 2nd 1998 pm; Pressure fell over The Bay of Biscay, causing light winds from the north-east. The accumulated pollution was then transported by these light winds towards the south-west.

The issues raised by the Meteorological Office on the performance of their NAME model in simulating this weather pattern will be discussed in Section 4.

Annex VI contains four additional meteorological diagrams.

What do the satellite photographs taken on this date show?

Table 3.8 Key to satellite photographs

FIGURE	3.7	3.8
Date	2-9-1998	
Satellite	NOAA 14	NOAA 12
Direction	Northbound	Northbound
Equator crossing time	13:36	16:53
Overhead time	13:52	17:09
Average altitude	856 km	816 km

The false colour satellite images on the next pages show a number of interesting features:

- The existence of clear skies in the high pressure region over Scandinavia;
- The cold front lying across the north sea;
- Stratification of the cloud across England in a north east to south west direction;
- A swirl of clouds over the Bay of Biscay.

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Figure 3.7 Satellite Photograph at 13:52 September 2nd 1998

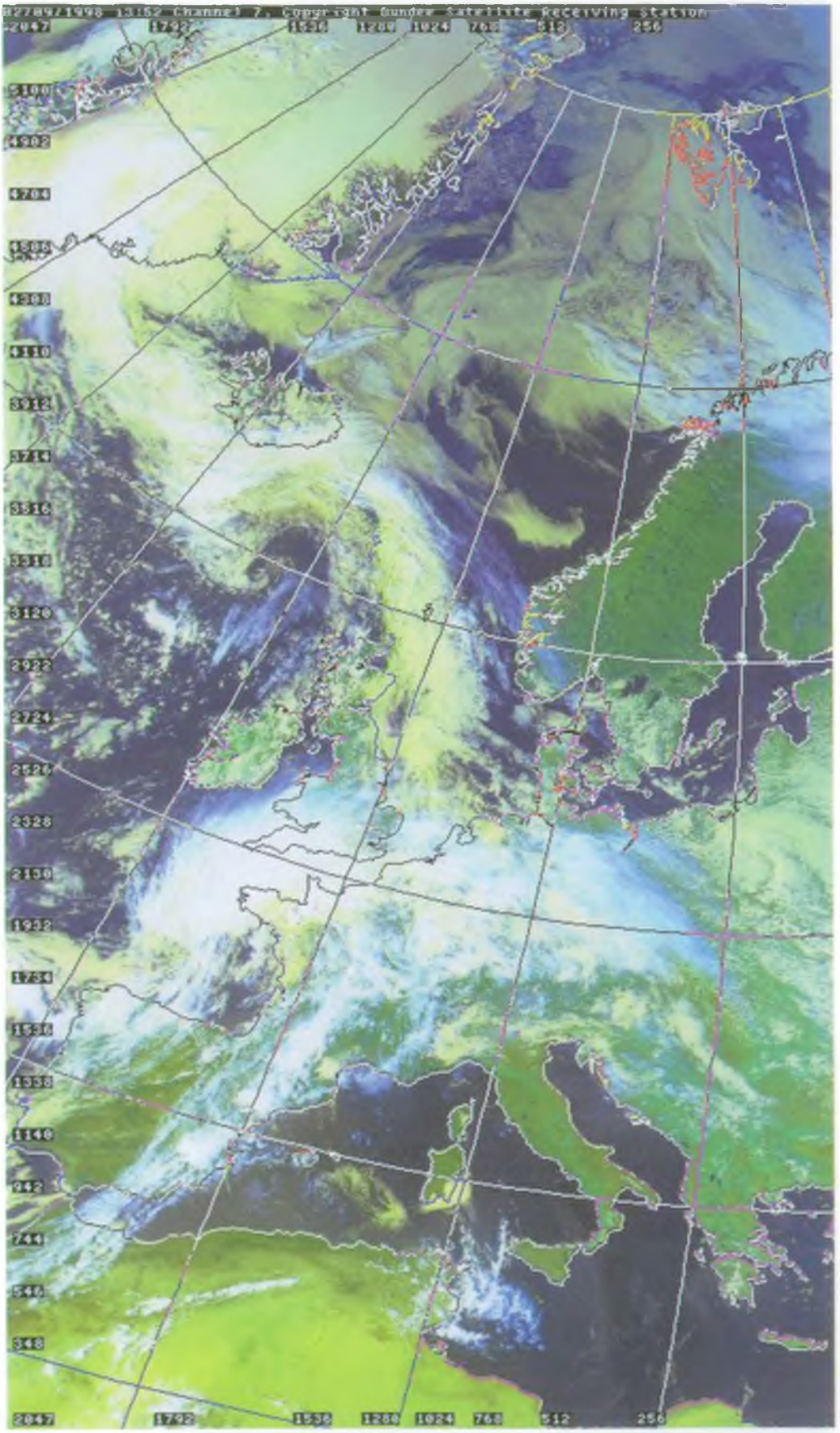
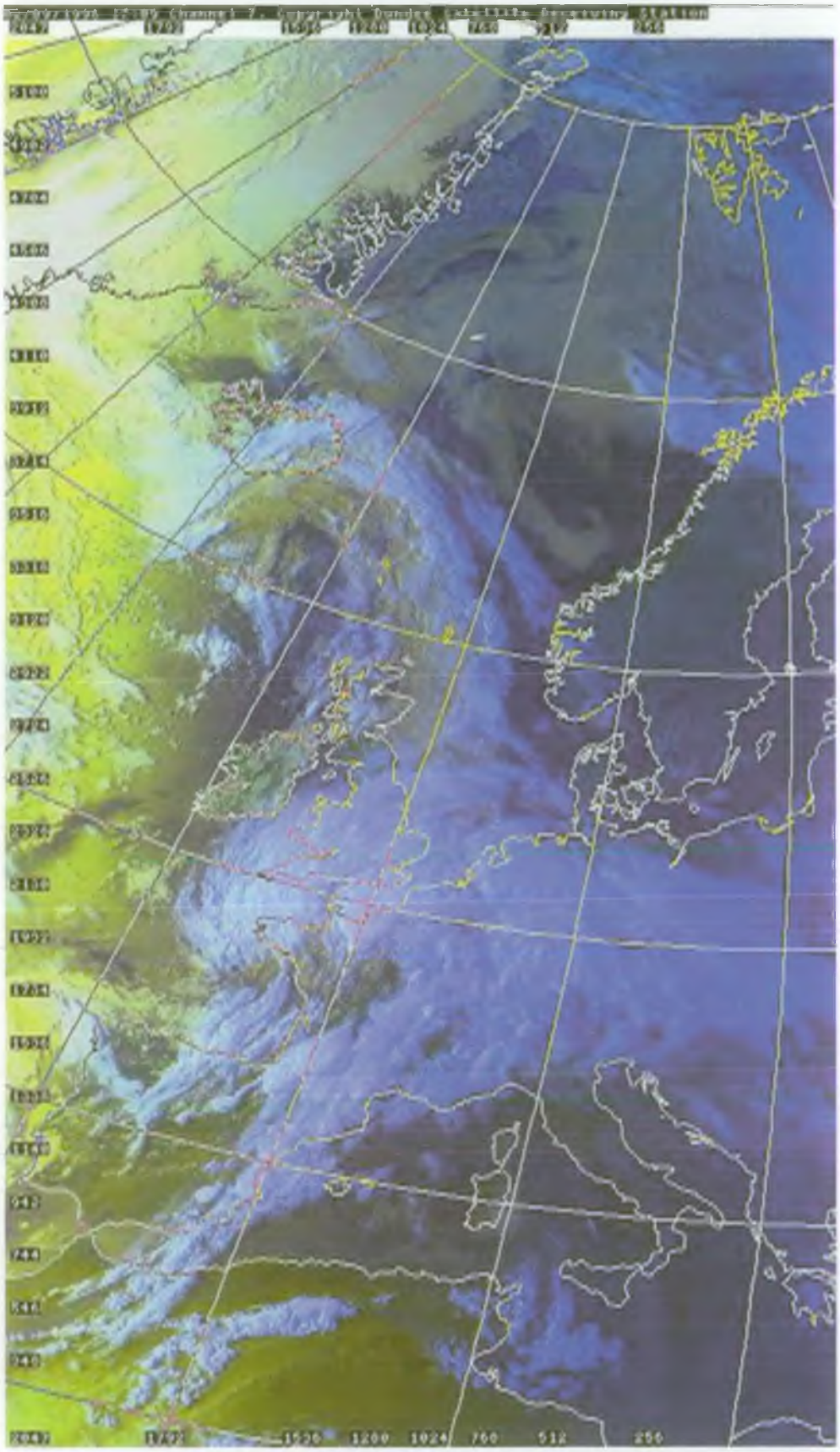


Figure 3.8 Satellite Photograph at 17:09 September 2nd 1998



4 Modelling

Summary

This section of the report explains why atmospheric dispersion modelling techniques were used as part of the investigation and looks at the limitations of this exercise and the types of information needed for it to run successfully.

The record of complaints and the results from sulphur dioxide monitoring stations indicate the progress of the pollution across the Midlands and South Yorkshire. However, these fail to identify the sources of the pollution or confirm the atmospheric mechanism that caused the episode.

The Agency examines the predictions made by the NAME model and compares them with actual monitoring station results. Simple statistical comparisons are used to provide a qualitative analysis of model performance.

In this section, the results of the atmospheric dispersion modelling using NAME are plotted in a variety of ways including:

- Concentration plots which show the average boundary layer concentration (as an hourly mean) of sulphur dioxide in hourly steps, these plots can then be used to estimate impact where there is no monitoring station nearby;
- Plume plots which show the particle age and current position, again, in hourly steps;
- The average sulphur dioxide concentration (as 15 minute mean) in the lower 50m of the atmosphere for each operating monitoring station in the study area in 15 minute steps;
- The contribution on average, and at the peak, to sulphur dioxide concentration at four selected DETR monitoring stations (Nottingham Centre, Birmingham Centre, Ladybower and Stoke-on-Trent) by the various modelled emission sources;
- The cross plume and upwind concentration at Nottingham Centre.

In this section each method is explained and the plots are used to show key observations and points of interest from the results. However, only selected plots are included - the full range is contained in Annex VII. The concentration and plume plots are also provided as an animated sequence on the CD-ROM.

Some weaknesses in the use of NAME have been identified by both the Met. Office and the Agency, including the selection of the industrial processes, and in the meteorological data and some of the specific calculations used by NAME. The Agency proposes to continue the investigation to overcome these identified weaknesses wherever possible.

What is the purpose of modelling for this investigation?

Because the DETR monitoring station network is limited, it cannot always track individual air pollution episodes and supply detailed information about them for analysis. The record of complaints and the results from sulphur dioxide monitoring stations indicate the progress of this air pollution episode across the Midlands and South Yorkshire. However, these fail to identify the sources of the pollution or confirm the atmospheric mechanism that caused the episode.

Numerical modelling of the plumes from the likely sources, i.e. those roughly upwind, was carried out to gain some insight into the dispersion process, help determine source culpability and to predict the likely concentrations in areas where no monitoring stations were actually located. This was carried out using NAME, an atmospheric dispersion model developed by the Met. Office.

What are the limitations of modelling?

It must be borne in mind when using a model, that the predicted results will never be a 'perfect' fit with reality. Atmospheric dispersion models make their predictions based on man's simplified understanding of the atmosphere, on how pollutants disperse within it and our ability to write computer programs that carryout the necessary arithmetic to produce some numerical results. Additionally, models require a great deal of input data: including source information such as pollutant release rates, the physical conditions of the release and, most importantly, detailed meteorology.

Therefore any model results are subject to a large degree of interpretation, and should not be viewed as an absolute rendition of reality, but as a guide only.

What models are available?

Most atmospheric dispersion modelling carried out by the Environment Agency is done using a United States Environment Protection Agency (USEPA) model called AERMOD, or a UK model called ADMS. They permit the modelling of airflow around buildings, the effects of terrain and coastline. They permit detailed analysis to be carried out over a range from a few 10's of metres to about 30 km. Additionally, they are both licensed by the Agency for use at many of the Agency offices, with many Inspectors trained in their use, and both are relatively quick to run. For these reasons the Environment Agency normally uses these models when modelling atmospheric releases from processes that it regulates.

However, these models are known as 'steady state' models. They deal with meteorology on an hour-by-hour basis, allowing, wind, for example, to blow only in a straight direction, and requiring many other meteorological parameters to be fixed for each hour as well. Pollution emitted in one hour is effectively ignored in the next; these types of model do not permit pollution to pool or accumulate in the atmosphere - a mechanism that is suspected to have occurred in this episode. Trial model runs using both AERMOD and ADMS illustrated their inability to predict the episode peak in Nottingham and were quickly abandoned for this investigation. An alternative type of model, much more suited to air pollution episode investigation was required for this investigation.

What alternative models are available?

NAME (Nuclear Accident ModEl) was initially developed by the Met. Office to model the dispersal of radionuclides in the atmosphere following a nuclear accident but is equally suited to modelling the everyday release of non-radioactive pollutants by industrial processes. NAME overcomes many of the limitations of steady state models and offers a greater flexibility and on this basis it was selected for use in this investigation.

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How does NAME work?

NAME is a numerical model run on a computer that handles the transport and dispersion of pollutants in the atmosphere. The actual emission of pollution from a source is represented using large numbers of 'pollution particles' that are released into a 'model atmosphere'. These particles represent a quantity or amount of pollution within a small volume of air (and must not be confused with particulate matter pollution (PM_{10})). The sources of pollution may be simple puff releases near the surface, or continuous releases, such as emissions from stacks. NAME allows the pollutants released in one hour to be still present in the atmosphere in subsequent hours, it allows wind direction to change and hence the flow of aggregated pollutants can appear curved.

The model atmosphere, represented by the winds and other meteorology, is obtained from the Met. Office's operational numerical weather prediction model, known as the Unified Model (UM). Given an initial meteorological condition, the model predicts all of the meteorology over the whole globe and over the time period of interest.

Each particle representing an air parcel with its small proportion of pollution is carried along and dispersed by the model winds. These transport and dispersion effects are carefully calculated to represent events in the real atmosphere as accurately as possible. At specified times the locations of the particles, with whatever airborne contaminant they are carrying, are used to calculate the air pollution concentration. Each particle is 'labelled' with the source that released it, so the source's contribution to the total concentration can be determined.

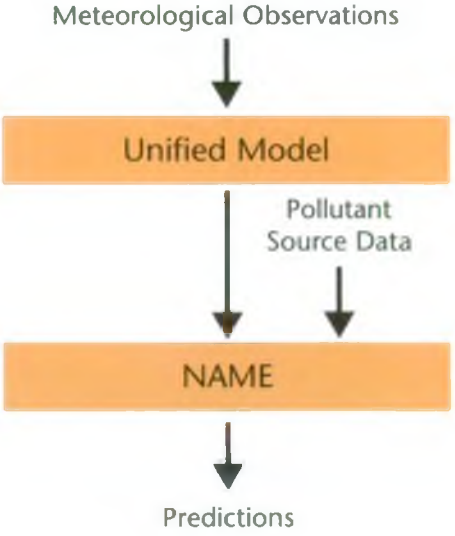
There are a number of ways that pollutants can be removed from the atmosphere and deposited onto the earth's surface. These include dry deposition, which is the result of impaction and sedimentation as pollutant-carrying air flows over the surface; and also wet deposition, which is the washout of pollutant to the surface by or in rainfall. Within NAME different calculations are used to represent frontal or showery rain, snowfall, and the enhancement of precipitation by hills. The model also handles various chemical changes, such as the oxidation of sulphur dioxide to sulphate.

What information is required to run NAME?

The two sets of input data critical for NAME are:

- Meteorology;
- Pollutant source data.

Figure 4.1 Data Requirements for NAME



Meteorology

The NAME model uses analysed 3-dimensional meteorological fields from the Unified Model, which give the best representation of the meteorology based on a short forecast run and available surface and satellite observations.

For this study, the NAME model was run using the mesoscale meteorological data from the UM. The area of the 1998[1] mesoscale model used covers the UK and NW France with a horizontal grid resolution of about 17km with the atmosphere vertically divided into 26 layers.

The meteorological data input into NAME from the UM changes on an hourly time-scale. The NAME model was run with a 15-minute time-step, over the 24 hour period of interest, with the meteorological data being interpolated in time between the hourly inputs.

How does the meteorology used by NAME compare with meteorological measurements?

At this point, it is important to examine the differences between the measurements actually recorded at Meteorological Stations and the weather conditions predicted by the UM and used by NAME for its dispersion calculations. It should also be noted that the NAME model has been run without 'accommodating' these differences which may affect the results.

The comparisons between NAME predictions and actual measurements made at a Met Office station near Nottingham are:

1. Wind speed

Wind speed is an important parameter in dispersion of pollutants. Low wind speeds can result in high concentrations; very low or stagnant conditions can allow pollutants to pool or accumulate in the atmosphere. On the other hand, normal to high wind speed can effectively disperse pollutants. In approximate terms, doubling wind speed will halve concentrations, and halve the time taken to travel from the source to a monitoring station.

Important points to note. Wind speed is:

- Apparently over-predicted during 04:00 to 08:00; wind speed at Nottingham Watnall was actually recorded as zero. However, the measurement of wind speed up to 1 m/s can be recorded as zero due to the inertia of the instrument. The model wind of 0.5 m/s is likely to be realistic, as there is likely to be some wind;
- Generally under predicted during 09:00 to 18:00;
- Over-predicted during 19:00 to the end of the day.

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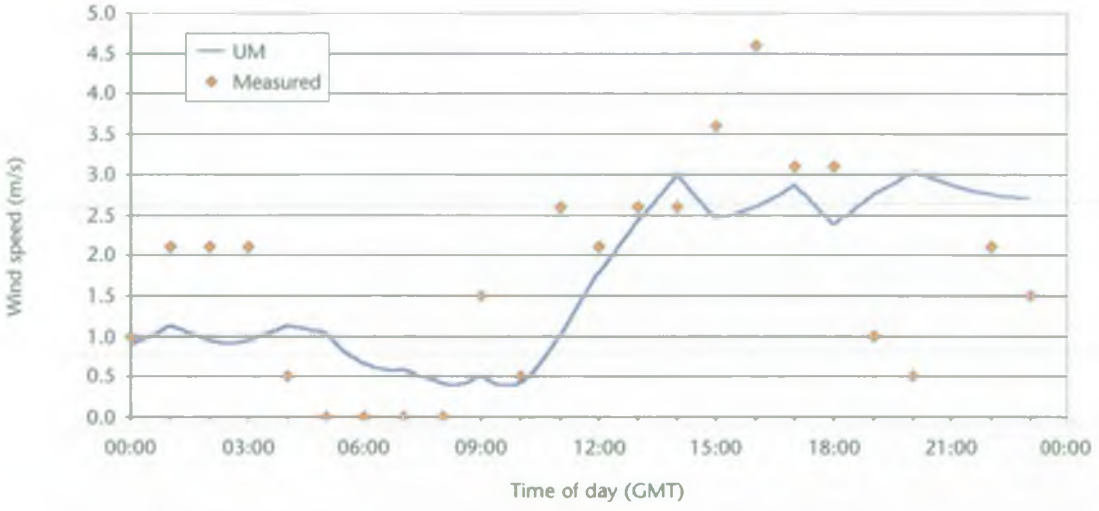
Figure 4.2 Wind speed at 10m, Nottingham Watnall, September 2nd 1998

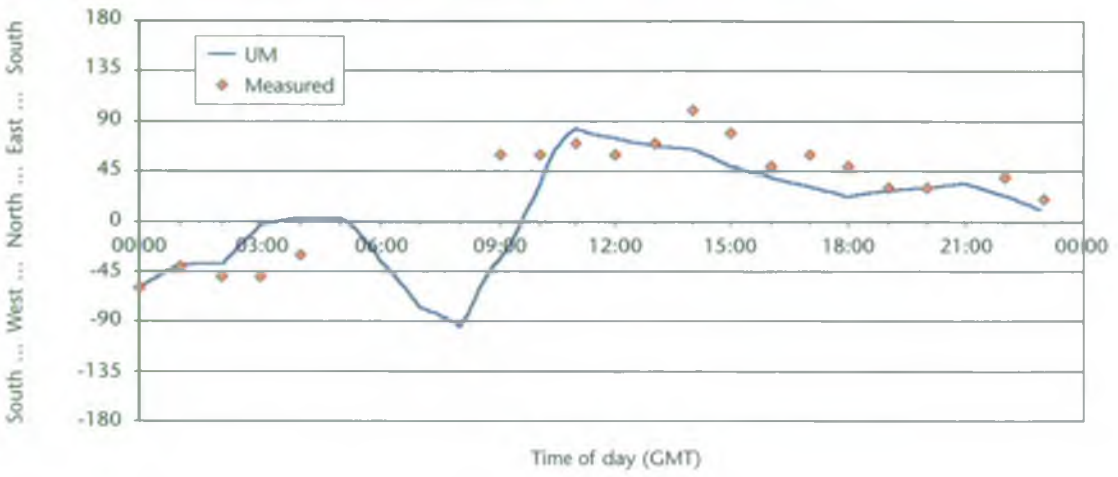


[1] Current mesoscale models have since changed.

2. Wind direction

Wind direction is obviously an important parameter as it describes where a pollutant travels to and hence where it will impact. A variation in the direction of travel may result in a plume entirely missing a given location and impacting upon another.

Figure 4.3 Wind direction at 10m, Nottingham Watnall, September 2nd 1998



Important points to note:

- On this figure a 0° is a wind from the north, 90° a wind from the east, -90° a wind from the west and 180° or -180° a wind from the south;
- A difference in direction that appears small on this graph, say 20° or so, could in fact, have a large effect.

There are no measured wind directions between 05:00 and 08:00 but the figure shows the NAME model wind direction. During this period wind speed was measured as zero (see Figure 4.2, wind speed, on page 26) making wind direction measurement impossible.

3. Boundary layer height

The boundary layer is important since it contains the air we breathe. The top of the boundary layer is defined by a temperature inversion that effectively traps pollutants within the boundary layer, and prevents migration of pollutants above the layer down to ground level. If the boundary layer is low enough then very tall stacks can release their pollution above the boundary layer; additionally very large, hot releases can have sufficient buoyancy to penetrate the inversion layer and so again be effectively transported above the boundary layer.

The height of the temperature inversion can be estimated from a meteorological diagram known as a tephigram. The data on a tephigram is measured during a so called sonde ascent in which a balloon with an instrument package is released and the measured data radioed back from the instruments. Two such diagrams are included in the meteorology annex (Annex VI) for Nottingham Watnall and show the boundary layer top at approx. 285 m above ground at 11:15 and 350 m at 17:15. The observed temperature line (shown in red) has been extracted from each diagram and enlarged to give the following two figures:

Figure 4.4 Enlargement from 11:15 Ascent

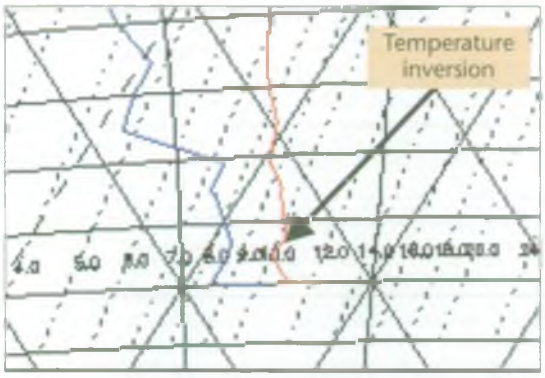
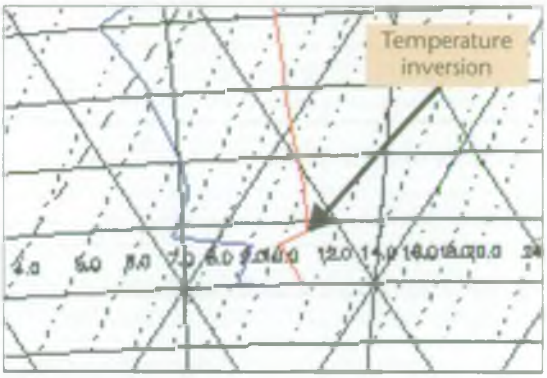


Figure 4.5 Enlargement from 17:15 Ascent



From these diagrams, the Met. Office calculates that a weak inversion layer existed at about 250 to 350m above the land surface, Nottingham Watnall being 117m above sea level. It is highly significant that the inversion was present at both 11:15 and 17:15 at similar heights.

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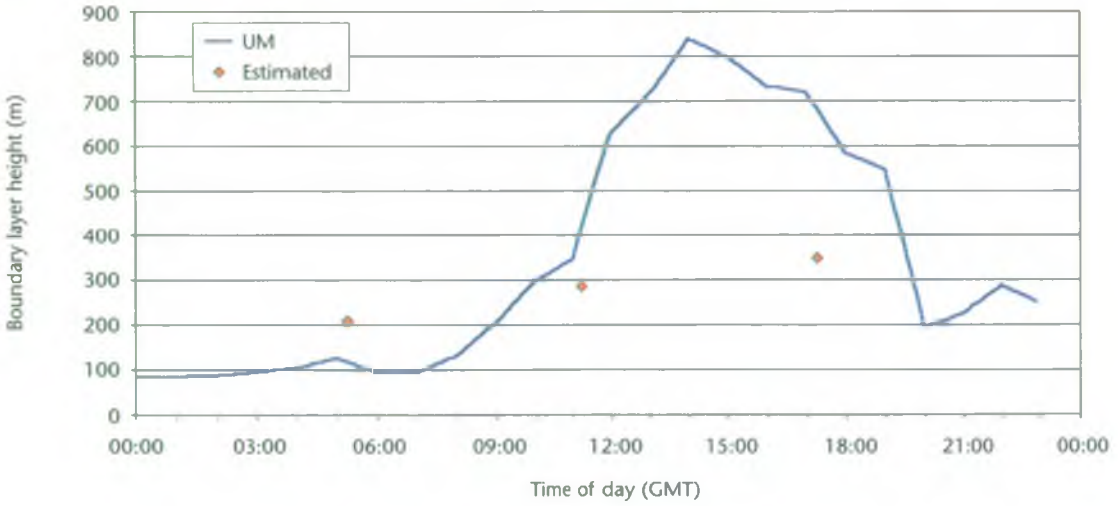
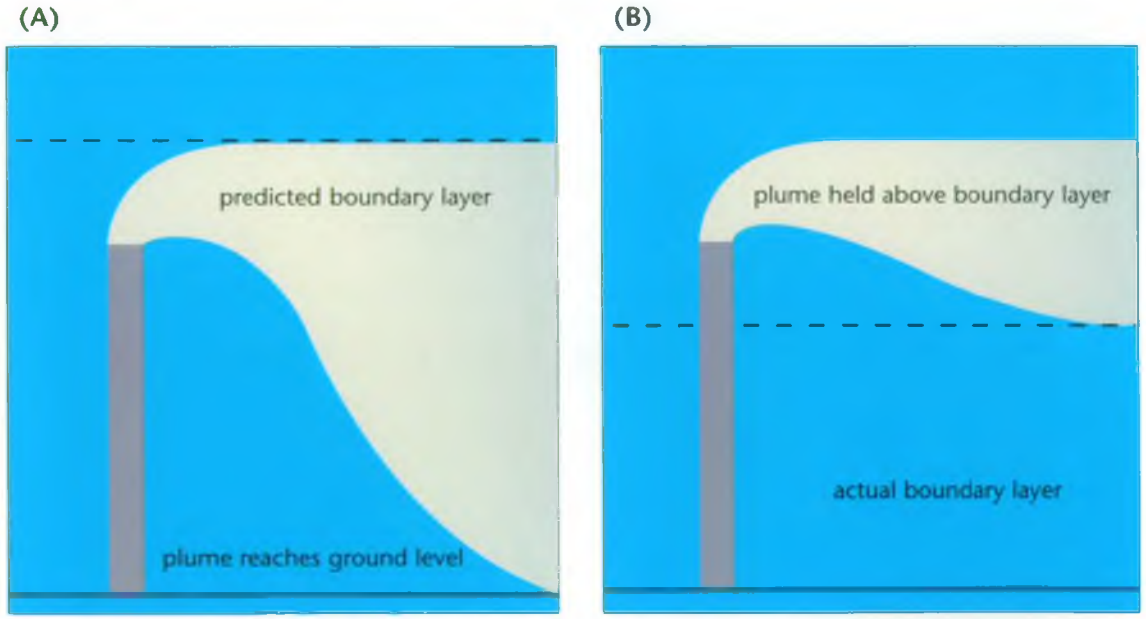
Figure 4.6 Boundary layer height, Nottingham Watnall, September 2nd 1998



The height of the top of the boundary layer estimated from the tephigrams at Nottingham Watnall are shown on Figure 4.6 with the UM's prediction at the DETR Nottingham Centre monitoring site. The UM boundary layer height is shown to rise up to about 800m (above ground level) during the afternoon. This difference might result in:

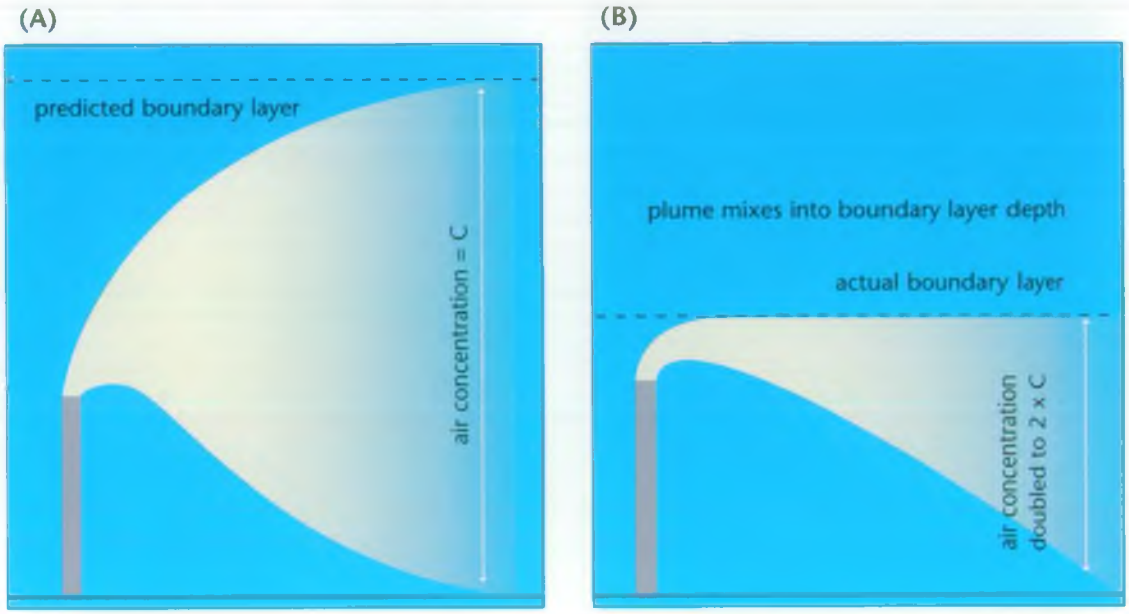
- Over-prediction by NAME as some stacks may have released pollutants above the actual boundary layer in reality - Figure 4.7 (B) - but below the predicted boundary layer in NAME - Figure 4.7 (A):

Figure 4.7 Effect of a release above or below the boundary layer



Under-prediction by NAME as the boundary layer is generally well mixed, a higher predicted boundary layer - Figure 4.8 (A) - top means that pollutant is diluted over a greater volume in NAME, than if the boundary layer height was lower - Figure 4.8 (B).

Figure 4.8 Effect of boundary layer height on concentration



How these two effects combine in practice is not known.

4

How were potential sources of pollution identified?

In order to numerically model the pollution episode, release data for the period leading up to and through the episode is required from those sources identified as being potential contributors.

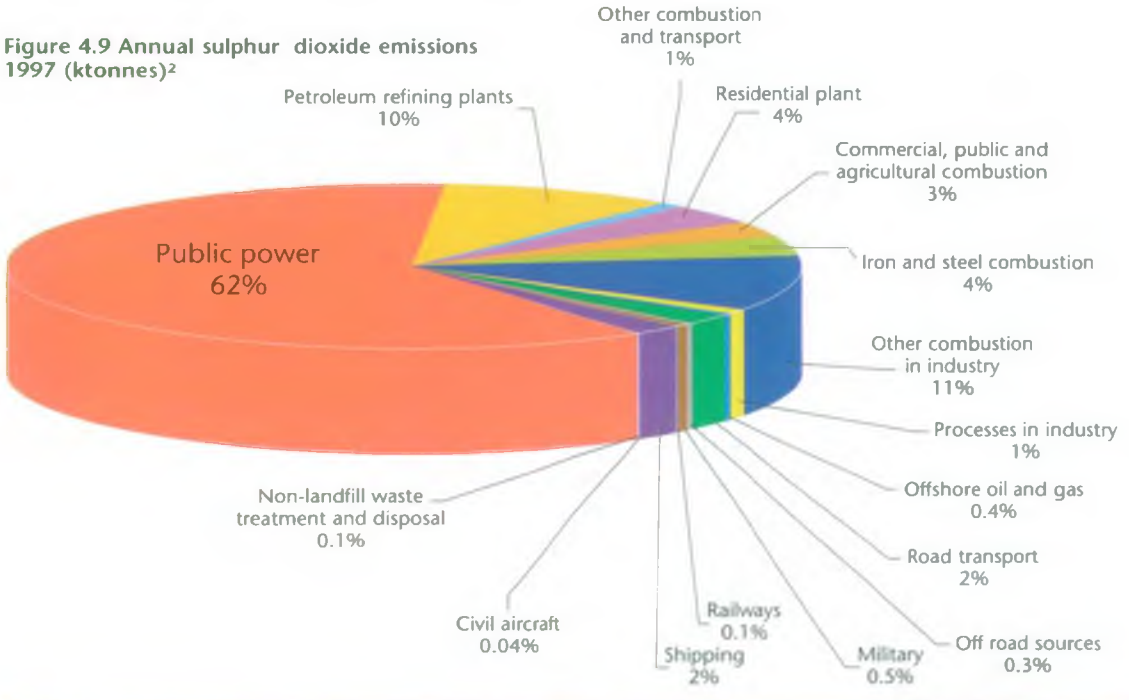
Sources include those which may be regulated by the Environment Agency under Integrated Pollution Control (IPC), or by a Local Authority under Local Authority Air Pollution Control (LAAPC) or the Clean Air Act 1993, or do not come under direct regulation (such as traffic or residential). In terms of amount released, Figure 4.9 indicates the relative importance of a variety of potential sources for the UK as a whole.

Which sources were selected for investigation?

Clearly, power generation, refineries, iron and steel and other major combustion processes (such as cement works and large industrial heating systems) are significant sources. They account for nearly 90% of the annual sulphur dioxide emitted in the UK. Other sources of sulphur dioxide are much smaller and geographically dispersed. Whilst these sources will have contributed to the air pollution episode, collecting the data from the major sources was believed sufficient for modelling purposes by the Agency. In practical terms, it would be difficult to collect all of the small source data.

However, consideration was also given to the potential presence of a LAAPC process or smaller heating system located close to and upwind of a monitoring station. If this was the case, then the recorded sulphur dioxide peak may have been disproportionately influenced by a relatively small source. However, no such LAAPC or heating systems could be identified. For example, the City of Nottingham Environmental Services informed the Agency that the nearest LAAPC process that was authorised to release sulphur dioxide was about 5 km to the north of the DETR Nottingham Centre monitoring station. At such a distance, and direction, it is most improbable that this source would have contributed significantly, if at all, to the Nottingham Centre peak. Similarly, the Local Authorities in Nottinghamshire as a whole have prepared an inventory of releases, which includes small heating systems. A search of this inventory did not reveal any sulphur dioxide sources that were close to and upwind of the monitoring site.

Figure 4.9 Annual sulphur dioxide emissions 1997 (ktonnes)[2]



[2] The Air Quality Strategy for England, Scotland Wales and Northern Ireland. Cm 4548, January 2000

Which Agency regulated processes were investigated?

The processes that required modelling were thus ones regulated by the Environment Agency. The release data available on the Agency's Pollution Inventory is an annual total. In order to carry out a detailed study for September 2nd 1998, hourly emission rates were required. In selecting possible processes that may have contributed to the episode, consideration was given to the size of the process and the distance upwind (towards the north east). In practice, data was collected from processes releasing sulphur dioxide within a box extending from Birmingham in the south west to Malton in the north east. Note that data was not collected from all processes authorised to release sulphur dioxide. For example the sugar factory in Newark was shut down during the entire day and Drakelow Power Station near Burton-on-Trent only commenced firing very late in the evening of September 2nd 1998. Data was collected from Ironbridge Power Station, but was not used in the NAME run since its westerly location implies it did not to contribute to the episode across the Midlands and South Yorkshire. This screening left the 16 processes shown in Table 4.1.

4

Table 4.1 Process selected for NAME modelling

LOCATION	PROCESS	OPERATOR*
Bolsover	Fuels	Coalite Products Ltd
Buxton	Cement	Tilcon (South) Ltd
Cottam	Power Generation	Powergen plc
Drax	Power Generation	National Power plc
Eggborough	Power Generation	National Power plc
Ferrybridge	Power Generation	Powergen plc
High Marnham	Power Generation	Eastern Merchant Generation Ltd
Hope	Cement	Blue Circle Industries plc
North Killingholme	Refinery	Lindsey Oil Refinery Ltd
Ratcliffe-on-Soar	Power Generation	Powergen plc
Rugeley	Power Generation	Eastern Merchant Generation Ltd
South Ferriby	Cement	Rugby Cement
South Killingholme	Refinery	Conoco (UK) Ltd
Scunthorpe	Iron and Steel	British Steel plc
West Burton	Power Generation	Eastern Merchant Generation Ltd
Willington	Power Generation	National Power plc

* The operator name given here was that used at the time of the episode. The ownership of some of these processes has changed, or the operator has changed name since then, or in the case of Willington, the site has now closed. Hence, in this report, the process location is used for identification purposes.

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The Environment Agency contacted each of the operators of these processes and asked for the following information:

- For each stack, its height, diameter and number of flues, flue diameter and National Grid Reference (NGR);
- For each stack, the average release rate of SO_2, NO_2, NO and particulates, temperature and release velocity (or volumetric flow) for each hour of the day for the September 2nd 1998;
- A commentary of plant performance, configuration or anything unusual on that day.

Many of the processes such as the cement and refineries are continuous with almost steady release conditions. Emissions from power stations modulate depending on the demand for electricity. They typically show a pattern of low generation in the early hours, increasing during the day, and then declining rapidly late evening. Obtaining the detailed release conditions is key to modelling this industry successfully.

None of the operators indicated any unusual operating conditions or informed the Agency of a breach of any IPC Authorisation condition on this day.

The release data supplied was collated and passed to the Met. Office for modelling using NAME.

Why are plume rise calculations significant for this investigation?

When gases are released from a stack with an upward speed or when they are hotter than the surrounding air, they tend to rise above the stack top. The speed provides the gases with momentum and the higher temperature provides them with thermal buoyancy. The momentum of the gases is reduced by friction and also as the plume mixes with the surrounding air, it cools and its thermal buoyancy reduces, with the result that the plume ceases to rise. Additionally, wind will cause the plume to bend and therefore to disperse both vertically and horizontally.

As a plume travels down-wind both the vertical mixing and horizontal spreading continue and the plume becomes fully mixed throughout the boundary layer. The effect of plume rise is of greatest importance at locations nearest to the source.

Wind speed and direction vary with height in the atmosphere. Hence, any overestimation or under estimation, of plume rise may affect NAME's ability to predict the path of the plume, the arrival time and air concentrations. This highlights the importance of an accurate calculation of plume rise.

Figure 4.10 Effect of plume rise on effective stack height

(A) with plume rise

(B) without plume rise

What is the status of NAME's plume rise scheme and how was it used?

The Met. Office's plume rise scheme is a simplified parameterisation of the actual processes taking place and to date, no thorough testing of their scheme has been undertaken. Consequently in order to model the situation correctly the effects of plume rise is included for comparison purposes.

The model results section that follows, concludes with two alternative comparisons of the concentrations at Nottingham Centre; the first excluding the effects of plume rise and the second using new methods currently under development.

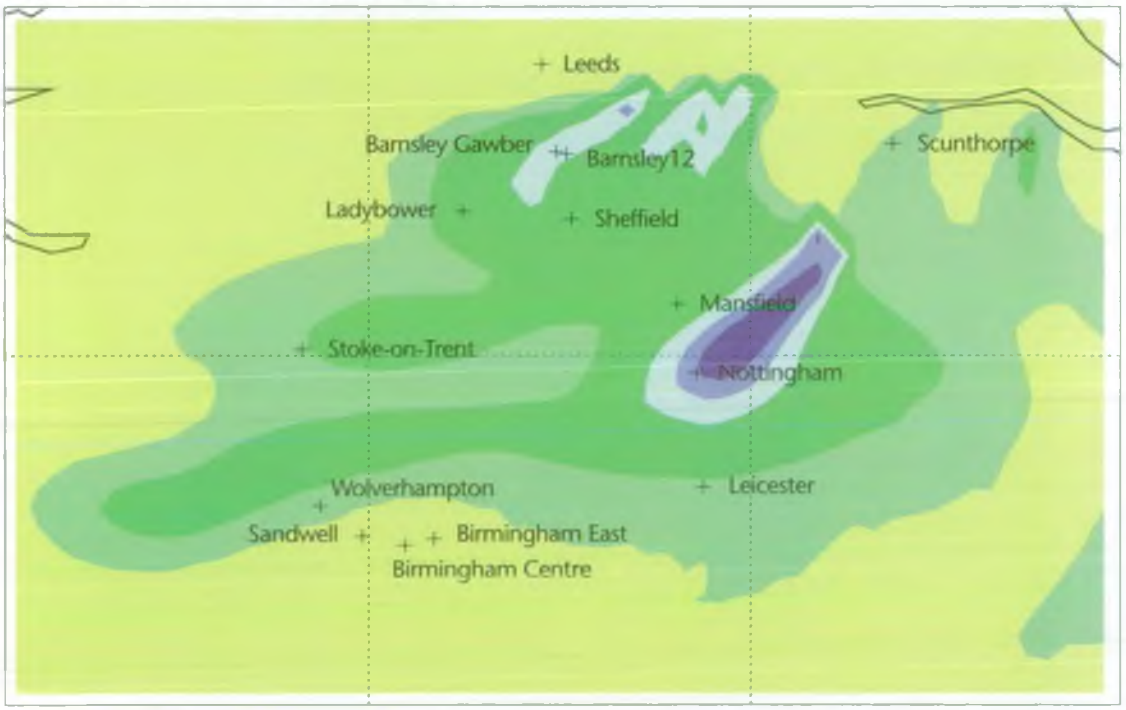
What are the detailed NAME model results?

The NAME model output can be displayed in a variety of ways for analysis:

Concentration plots

The complete series of concentration plots is given in Annex VII (together with the plume plots). The following is an example of the boundary layer concentration plot, showing the atmospheric hourly mean concentration of sulphur dioxide.

Figure 4.11 Concentration plot for 16:00 GMT



Concentration key

Below air quality standard	Above air quality standard
< 1 ppb	100 – 200 ppb
1 – 10 ppb	200 – 300 ppb
10 – 100 ppb	300 – 400 ppb
	> 400 ppb

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The concentrations are given as hourly means whereas the air quality standard for sulphur dioxide is a 15 minute mean. However, for the standard concentration to be exceeded over one hour means that it must have been exceeded during at least one of the four 15 minute periods making up that hour. Thus, the colour banding is an optimistic indication of where the 15 minute standard was exceeded.

The plot also shows the monitoring stations where detailed comparisons have been carried out. You may notice that the plot appears slightly squashed vertically. This is because the NAME plotting routine works on equal degrees of latitude and longitude whilst in practice, for the UK, a degree latitude actually equates to a much greater physical distance than a degree longitude which results in a 'squashed' appearance on the map.

These concentration plots are predictions containing a great deal of detail and are therefore difficult to summarise; however they serve to highlight several points of interest and a fully animated sequence of these plots showing the progress of the pollution can be found on the CD-ROM.

Points of interest include:

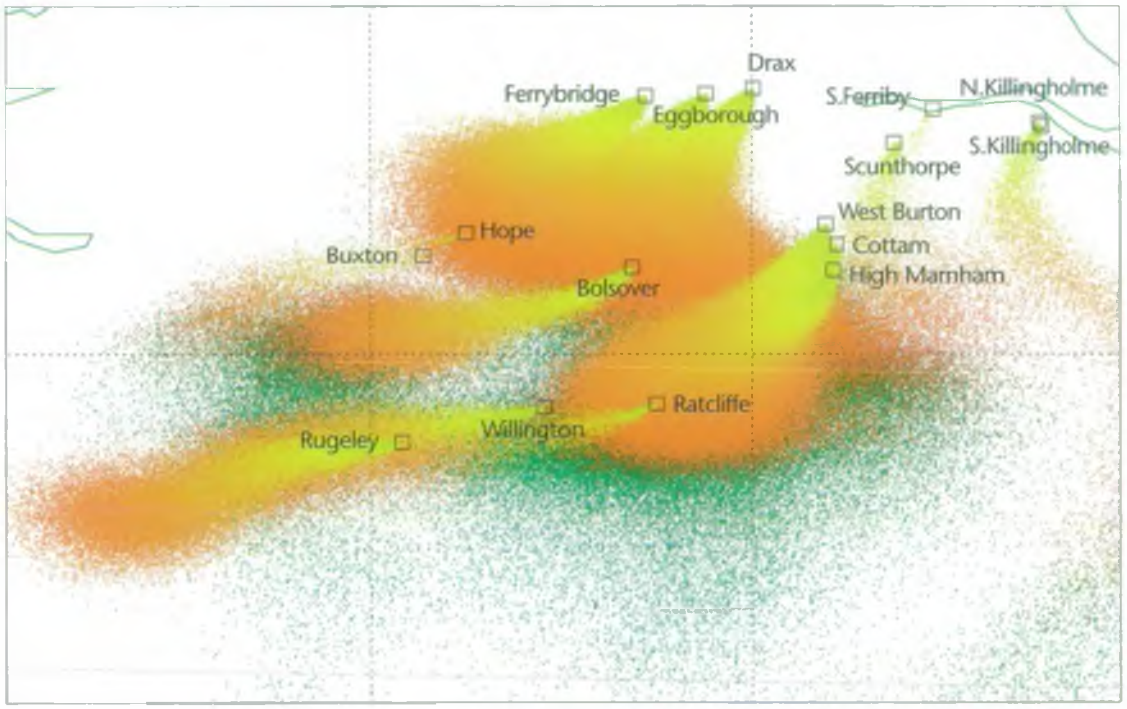
- The first plots in the sequence show mainly the continuous processes in operation, with only a few of the power stations operating. Sulphur dioxide concentrations are highest around the source at Bolsover;
- Between 04:00 and 09:00 GMT more sources become operational and wind speed has dropped to near zero, allowing sulphur dioxide to accumulate in the atmosphere;
- From 10:00 to 15:00 GMT the wind speed has increased and changed to north easterly. These light winds and other changes such as the increase in boundary layer height, dilute the accumulated sulphur dioxide. This is particularly noticeable around the sources at Bolsover, Rugeley and Willington;
- Around 16:00 GMT, the plume travelling from north Nottinghamshire and the Humber bank arrives at Nottingham City;
- At 19:00 GMT, the plume passes to the south of Nottingham; it is interesting to note how narrow the predicted plume appears. It could be speculated that it could pass between the Nottingham Centre and Leicester Centre monitoring stations without detection;
- Around 21:00 GMT the plume reaches the Birmingham area;
- At 23:00 GMT the plume still exists (although the highest concentrations predicted are < 200 ppb as an hourly mean) but now misses all of the monitoring stations except Nottingham where the edge of the plume still crosses the monitoring station;
- The plumes from North and South Killingholme do not appear to be significant. This is illustrated by the 18:00 GMT plot that shows the plumes tracking roughly southwards without reaching far enough west to pass over Nottingham.

Plume plots

Earlier in this section there was a description of how NAME models the transport and dispersion of pollutants by using 'particles' to represent quantities of atmospheric pollutants. As NAME performs its calculations, these particles are moved by the model winds. At any time, the position of each particle is known, and can be used to determine the time elapsed since the particle was released, in other words, the particle's age. NAME displays this information onto what is known as 'plume plots' showing particle position and using colour to indicate particle age. Each plume plot shows the sixteen sources investigated and corresponds with a concentration plot for a given time. For example, Figure 4.12 shows the plume plot that corresponds with the concentration plot given in Figure 4.11, on page 34.

These are two-dimensional plots of what within NAME is a 3 dimensional representation of the atmosphere.

Figure 4.12 Plume plot for 16:00 GMT



Particle age key

0-2 hours	12-14 hours
2-4 hours	14-16 hours
4-6 hours	16-18 hours
6-8 hours	18-20 hours
8-10 hours	20-22 hours
10-12 hours	22-24 hours

The complete range of plume plots and corresponding concentration plots are contained in Annex VII.

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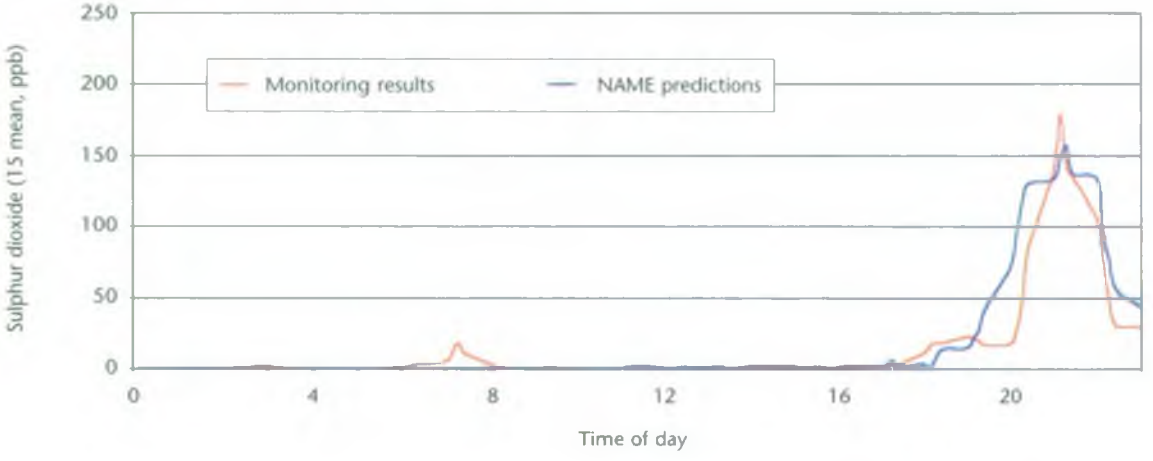
Comparison with monitoring station' data

Annex VII also contains a series of figures that compare the predicted NAME air concentrations with those measured at the monitoring stations. The stations active during the episode were:

1. Barnsley 12
2. Barnsley Gawber
3. Birmingham Centre
4. Birmingham East
5. Ladybower
6. Leicester City
7. Mansfield
8. Nottingham Centre
9. Sandwell
10. Scunthorpe
11. Sheffield
12. Stoke-on-Trent
13. Wolverhampton

For example, Figure 4.13 shows the comparisons for Birmingham East:

Figure 4.13 DETR Birmingham East September 2nd 1998



This match between monitoring results and NAME prediction is considered exceptionally good, taking into account that only the 16 most significant sources have been included in the input data for NAME and other more diffuse sources such as traffic and urban releases have not been included. This explains why each figure often shows low levels of monitored sulphur dioxide concentrations where NAME predicts none. Figure 4.13 illustrates this, with NAME substantially predicting zero sulphur dioxide concentration before 16:00 GMT whereas the monitoring station detected between 2 and 19 ppb.

Annex VII also contains some simple statistical comparisons of monitoring station data for the other 12 monitoring stations with a small commentary against each graph. The match between observations and NAME predictions is good for some locations and poor for others.

Overall, a qualitative assessment indicates that the atmospheric dispersion model used (NAME) is performing as would be expected of a current state-of-the art atmospheric dispersion model.

How does NAME analyse source culpability?

As each particle released into the NAME simulated atmosphere is labelled with its time of release and its source, at any given point and time it is possible to calculate the air concentration of pollutants and also the source of the particles. For this report, NAME was used to predict contribution for all of the sources modelled, at four DETR monitoring stations broadly spanning the study area: Nottingham Centre, Birmingham Centre, Ladybower and Stoke-on-Trent.

What was the aggregated contribution for each of the sources?

Table 4.2 shows the NAME predicted aggregated sulphur dioxide mass (as a percentage of the total) at each of the four monitoring stations for the period 11:00 to 23:00 GMT for the lowest 50m above ground of the boundary layer.

Table 4.2 Aggregated sulphur dioxide mass for the period 11:00 to 23:00 for the lowest 50m of the boundary layer
The number of significant figures used is not indicative of accuracy; a blank entry denotes no contribution.

SOURCE	BIRMINGHAM CENTRE %	LADYBOWER %	NOTTINGHAM CENTRE %	STOKE-ON-TRENT CENTRE %
Bolsover			0.05	40.27
Buxton				0.98
Cottam	38.50		32.90	
Drax	11.27		6.49	
Eggborough	0.78	0.84	0.52	4.51
Ferrybridge	0.97	99.16	1.46	53.29
High Marnham	10.69		7.86	
Hope				0.95
North Killingholme				
Ratcliffe	4.76			
Rugeley				
South Ferriby			0.02	
South Killingholme				
Scunthorpe			0.09	
West Burton	33.03		50.61	
Willington				

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What were the source contributions to individual peaks?

Tables 4.3 to 4.6 show the percentage contribution in the lowest 50m of the simulated atmosphere at the peak time only. Percentage contribution is at peak time only and is based on ppb (ie volume ratio). The number of significant figures used is not indicative of accuracy.

Table 4.3 Birmingham Centre sulphur dioxide mass at peak concentration
Peak at Birmingham Centre was at September 2nd 1998 21:30 GMT.

SOURCE	CONTRIBUTION AT PEAK %	MAXIMUM TRAVEL TIME	MINIMUM TRAVEL TIME	MEAN TRAVEL TIME
		HOURS: MINUTES		
Bolsover	0			
Buxton	0			
Cottam	40.57	17:44	07:09	10:46
Drax	8.69	21:59	15:06	18:11
Eggborough	1.42	16:12	15:04	15:28
Ferrybridge	1.52	22:13	18:02	20:04
High Marnham	13.52	15:37	06:50	09:17
Hope	0			
North Killingholme	0			
Ratcliffe	2.80	05:38	02:57	03:57
Rugeley	0			
South Ferriby	0			
South Killingholme	0			
Scunthorpe	0			
West Burton	31.47	16:48	07:15	11:38
Willington	0			

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Table 4.4 Ladybower sulphur dioxide mass at peak concentration
Peak at Ladybower was at September 2nd 1998 17:00.

SOURCE	CONTRIBUTION AT PEAK %	MAXIMUM TRAVEL TIME	MINIMUM TRAVEL TIME	MEAN TRAVEL TIME
		HOURS: MINUTES		
Bolsover	0			
Buxton	0			
Cottam	0			
Drax	0			
Eggborough	0.56	07:02	07:02	07:02
Ferrybridge	99.44	12:48	05:00	07:16
High Marnham	0			
Hope	0			
North Killingholme	0			
Ratcliffe	0			
Rugeley	0			
South Ferriby	0			
South Killingholme	0			
Scunthorpe	0			
West Burton	0			
Willington	0			

Table 4.5 Nottingham Centre sulphur dioxide mass at peak concentration
Peak at Nottingham was at September 2nd 16:15.

SOURCE	CONTRIBUTION AT PEAK %	MAXIMUM TRAVEL TIME	MINIMUM TRAVEL TIME	MEAN TRAVEL TIME
		HOURS: MINUTES		
Bolsover	0			
Buxton	0			
Cottam	47.05	10:01	04:35	05:45
Drax	2.33	16:54	11:54	14:43
Eggborough	0.18	09:58	09:58	09:58
Ferrybridge	2.39	16:01	11:17	14:22
High Marnham	13.92	07:29	02:39	04:29
Hope	0			
North Killingholme	0			
Ratcliffe	0			
Rugeley	0			
South Ferriby	0			
South Killingholme	0			
Scunthorpe	0			
West Burton	34.13	11:36	04:19	07:09
Willington	0			

Table 4.6 Stoke-on-Trent sulphur dioxide mass at peak concentration
The peak at Stoke-on-Trent is very difficult to determine (see the graph comparing measured concentrations and NAME predictions in Annex VII). This table gives the % contribution at 23:00.

SOURCE	CONTRIBUTION AT PEAK %	MAXIMUM TRAVEL TIME	MINIMUM TRAVEL TIME	MEAN TRAVEL TIME
		HOURS: MINUTES		
Bolsover	0			
Buxton	0			
Cottam	0			
Drax	0			
Eggborough	10.80	13:17	09:24	11:01
Ferrybridge	87.30	17:36	08:15	10:40
High Marnham	0			
Hope	1.90	04:15	04:06	04:11
North Killingholme	0			
Ratcliffe	0			
Rugeley	0			
South Ferriby	0			
South Killingholme	0			
Scunthorpe	0			
West Burton	0			
Willington	0			

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Points to note about the culpability analysis:

- Cottam, High Marnham and West Burton were the majority contributors to the Birmingham and Nottingham peaks;
- Ferrybridge was the main cause of the peak at Ladybower and Stoke-on-Trent;
- Drax contributed more to the Birmingham peak than at Nottingham;
- Eggborough contributed more to Stoke-on-Trent than Ladybower;
- The travel times illustrate how slowly the air mass was moving during the day; it took about 10 to 20 hours for the sulphur dioxide released to travel across the region. These transit times are one reason why 'steady state' models are unusable for this investigation as they effectively work on an hour by hour basis and do not allow pollutants to pool or accumulate.

Cross-plume and upwind concentrations for Nottingham

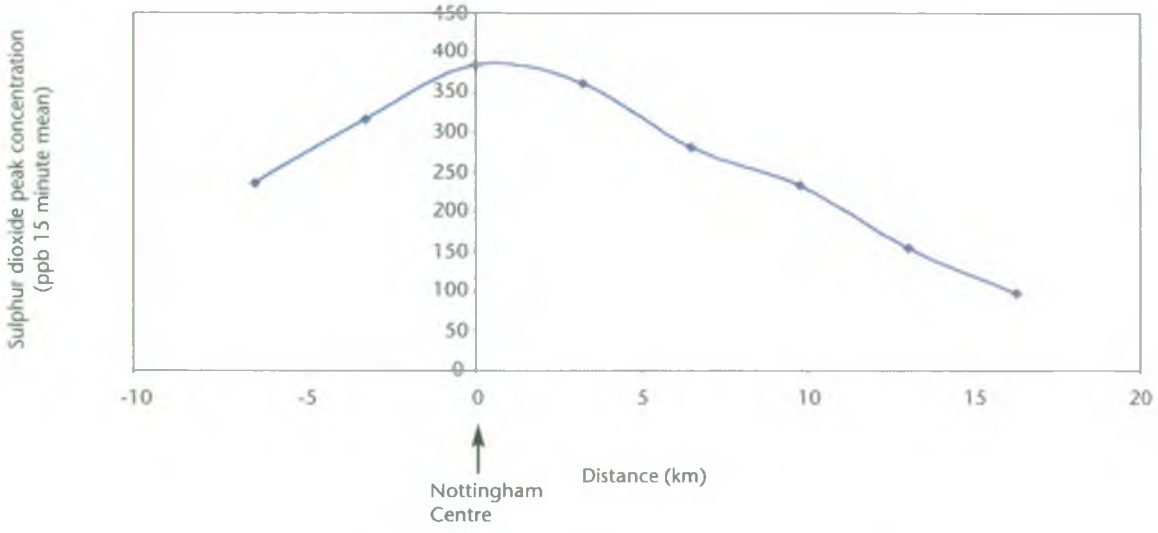
The Nottingham Centre sulphur dioxide peak was measured as 653 ppb, whilst the NAME peak prediction (without plume rise) was 385 ppb and also timed approximately one hour earlier. Possible explanations for this difference are considered later in this report, however, it raised two important questions for which specific output was generated by NAME when searching for an explanation. These questions are considered in the following section.

4

What is the cross-plume concentration?

The possibility exists that the predicted plume path 'misses' Nottingham and travels to one side of Nottingham, producing a lower prediction. Figure 4.14 shows the NAME predictions for the cross-plume concentration i.e. the concentration at right angles to the plume's direction of travel, for the lowest 50m of the atmosphere:

Figure 4.14 Peak cross-plume concentration at Nottingham

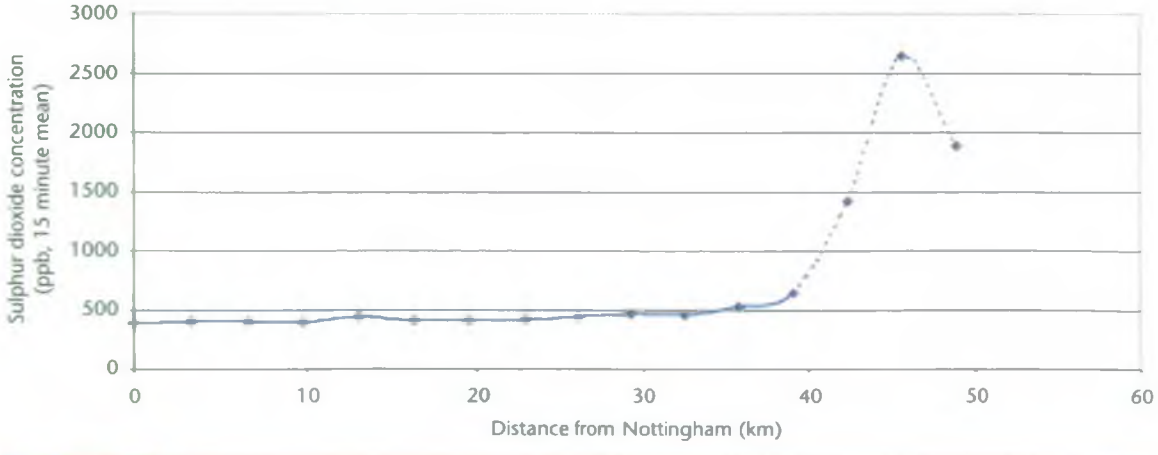


The horizontal axis on the diagram runs from approximately the north-west (negative) towards the south-east (positive). It shows that NAME predicts the plume centre-line to be roughly over Nottingham Centre.

What upwind concentrations are predicted between Nottingham and the area of the North Trent power stations (High Marnham, Cottam and West Burton sources)?

This question is raised due to the fact that the area between Nottingham and the power stations is inhabited but no DETR monitoring stations are located there. In this case, the prediction of sulphur dioxide concentration could show that the Nottingham Centre peak possibly occurs as part of an upwind concentration. The horizontal axis on figure 4.15 is distance from Nottingham Centre (at zero) towards the north-east (approximately). It shows very little variation in predicted (in the lowest 50m of the atmosphere) peak concentration except within the areas near to power stations. The predictions close to the stations must be treated with caution as NAME was run without using plume rise calculations which would result in over-estimation of ground level concentrations near to the sources - the curve is shown as dotted on the graph for this reason. The flat profile of the results closer to Nottingham indicates that no substantial variation in the predicted peak was occurring immediately upwind.

Figure 4.15 Upwind peak concentration from Nottingham



What are the effects of plume rise scheme on modelling concentrations at Nottingham?

The modelling reported previously has been carried out by the Met. Office without the inclusion of NAME plume rise calculations. However, NAME was also run with a new plume rise scheme currently under development by the Met. Office.

The following figures show the comparisons between the DETR monitoring station measurements (red) and NAME predictions (blue) for the no plume rise and the new plume rise scheme cases:

Figure 4.16 DETR Nottingham Centre – no plume rise scheme

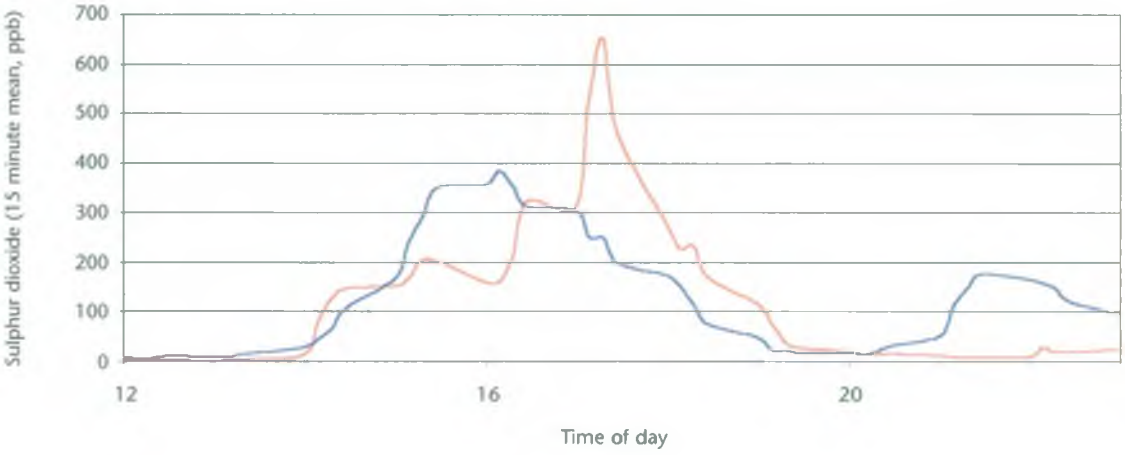
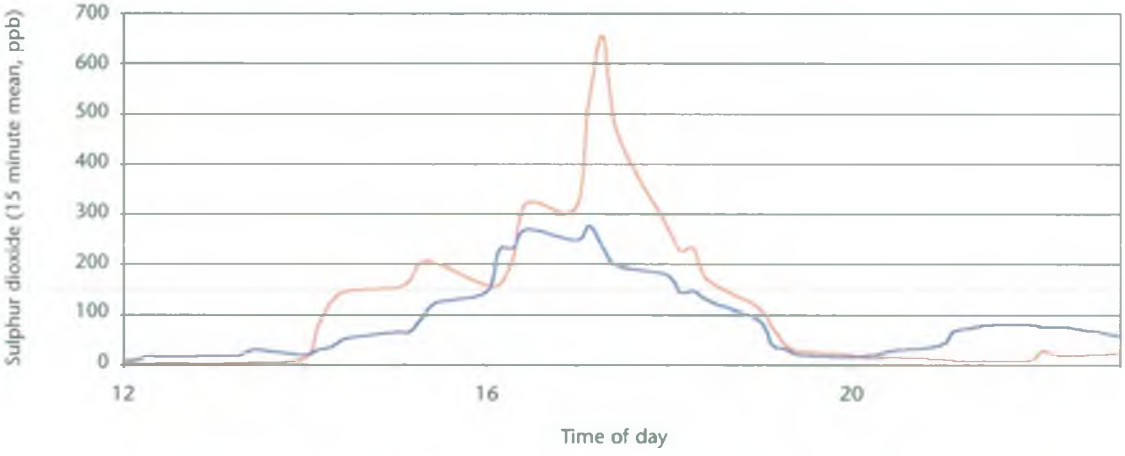


Figure 4.17 DETR Nottingham Centre – new plume rise scheme



The differences between the two graphs can be explained by the fact that wind direction and speed varies with height in the atmosphere. The inclusion of plume rise effects means that the stack plumes reach greater heights and are affected by different wind strengths and directions. Plume rise can also mean that a plume may penetrate through the top of a low boundary layer rather than mixing within it. This results in the plume remaining above the boundary layer until the boundary layer grows vertically high enough to encompass it.

The Environment Agency recognises the importance of the plume rise scheme for the analysis of air pollution episodes and will monitor the development of the more recent NAME plume rise scheme.

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What is the outcome of the modelling analysis?

The performance of NAME is comparable with other currently available atmospheric dispersion models. It predicts, for most DETR monitoring stations, the arrival time, peak time, departure time of the air pollution and the peak concentration. Accepting that the model results are reasonable, it allows the examination of the model predictions of concentrations in areas where no DETR or LA operated monitoring stations are located.

The highest concentration by far occurred at Nottingham. Although it is predicted to within a factor of two, the peak concentration at Nottingham is low compared with the actual peak recorded. The Agency considered the following possible explanations for this error:

- **The existence of other sources contributing sulphur dioxide that were not included in the modelling:**

  In carrying out the preparation for the modelling, the Agency considered many other smaller sources of sulphur dioxide, but established that none of these could have significantly influenced the results from the Nottingham Centre DETR monitoring station, therefore they were not included in this investigation.

- **An individual source emitting significantly more sulphur dioxide than was reported to the Agency, by the operator:**

  There is no evidence that any of the sources emitted more sulphur dioxide than reported. The magnitude of the difference between measured and predicted values, suggests that no individual process could realistically emit the quantity of sulphur dioxide required to cause the peak excess.

- **A failure or interference occurred to the Nottingham measuring equipment:**

  The evidence, given in Section 3, shows that hydrocarbon interference, due to atmospheric hydrocarbon levels, or to measuring instrument failure did not occur at the Nottingham Centre monitoring station.

- **Failure of NAME to correctly model the release (i.e. plume rise) or transport of the pollution:**

  The NAME model is driven by the meteorological data from the UM which has a resolution of 17 km therefore highly localised meteorological effects cannot be fully represented. It is possible therefore that the NAME model could be under estimating the Nottingham Centre peak for a number of reasons:

  - Over-prediction of wind-speed between 04:00 and 08:00 GMT:

    The over prediction of wind speed is unlikely. Comparison of the model winds over the Nottingham area with those measured at Nottingham Watnall is useful but the measurement site is not representative of the whole area.

  - The model is unable to resolve localised fluctuations in concentration:

    The NAME model concentration at Nottingham is the result of averaging over a finite volume (approximately 5km x 5km x 50m). In reality the plume concentration is likely to have some structure over this scale resulting from localised meteorological and topographical variations. The NAME model will not be able to resolve these local effects and provides an average value for the area. Ideally, the NAME output would be compared with an average of several measurement sites over Nottingham in order to establish the average concentration over the city.

- Over-prediction of boundary layer height:

  Evidence from the Nottingham Watnall tephigrams, suggests that NAME greatly over- predicted the boundary layer height during the afternoon of September 2nd 1998 in the Nottingham area. Over-prediction of the boundary layer height could result in either an over-estimation or under-estimation of ground level concentrations. On this occasion the Met. Office holds the view that the prediction of a more dilute plume is most likely. In reality this means that with approx. half the boundary layer depth available, potentially, the ground level concentration could be doubled.

Additionally, whilst poor performance is noted at some stations, notably Scunthorpe and the Mansfield DC, both these stations are relatively close to modelled sources and therefore the use of modelling without the effects of plume rise, will adversely influence the predictions for these stations.

What conclusions can be drawn?

Although these modelling conclusions cannot be confirmed, the Agency currently considers on the balance of probabilities that:

- the peak at Nottingham Centre can be explained by the division of culpability given in table 4.7:

Table 4.7 Source culpability for the Nottingham Centre peak

	%	MEASURED PEAK PPB
Total	100	635
Cottam	47	298
High Marnham	14	89
West Burton	34	216
Others	5	32

- under-prediction by NAME at Nottingham Centre is a function of the meteorology used in the model, specifically the boundary layer height;
- the contribution from all other low-level sources is so small as to be insignificant.

In view of the identified weaknesses within the modelling of the episode and its analysis, the Agency proposes to continue the investigation to overcome these wherever possible.

Whilst the final part of this analysis has focused on the peak measured at Nottingham Centre (because it was by far the most significant) it must not be forgotten that many other places experienced peaks above the EPAQS air quality standard.

4

5 Future reduction in sulphur dioxide emissions from coal fired power stations

Summary

This section outlines the approach the Environment Agency has taken to the control of air pollution, arising, in particular, from releases of SO_2 from the nineteen coal and oil fired power stations in England and Wales. These stations were originally authorised in 1993 by Her Majesty's Inspectorate of Pollution (HMIP)* and the controls placed on them were revised in 1996 by the Environment Agency.

In October 1998, the Government published its new energy policy, which aims to ensure safe, diverse and sustainable supplies of energy and control air pollution. In the light of developments to this energy policy and further public consultation, the Agency subsequently reviewed the emission of pollution from coal and oil-fired power stations and placed new controls on individual stations. With these in place, it is expected that power station emissions of sulphur dioxide will reduce by approximately 60% and that the objectives of the Government's National Air Quality Strategy, particularly in relation to sulphur dioxide, will be achieved by 2005 as required. This will reduce the frequency and intensity of air pollution episodes, including the occurrence of more significant episodes such as this one.

* HMIP a predecessor organisation to the Environment Agency

What sulphur dioxide emission controls exist on power stations in England and Wales?

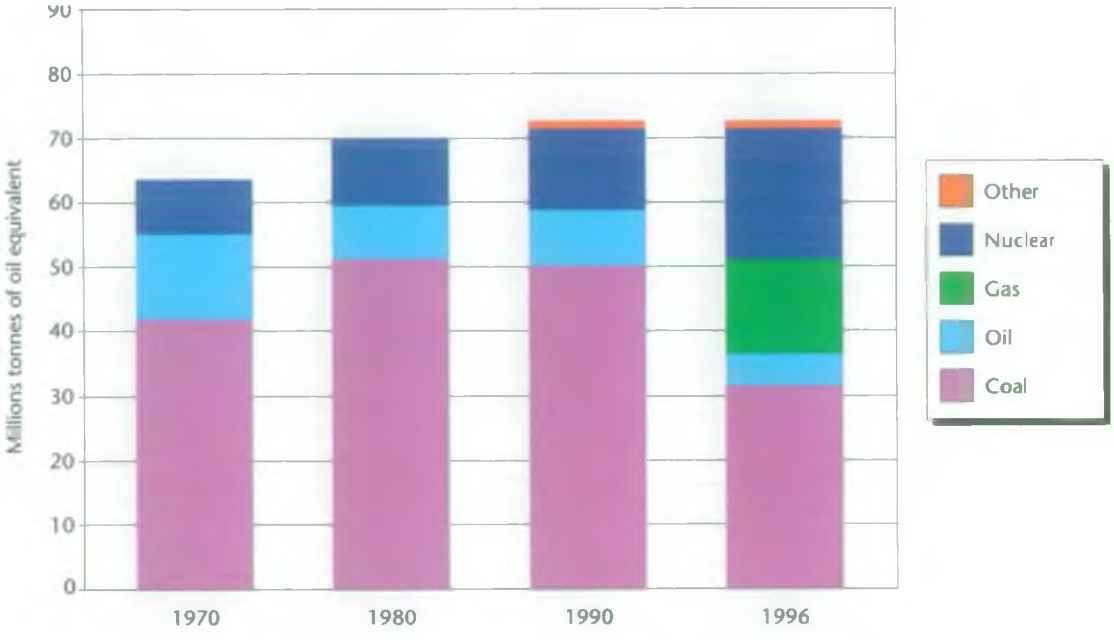
Releases of sulphur dioxide from power stations were controlled by a system of 'A' and 'B' limits and also, a limit on the sulphur content of fuel burnt at the station.

The 'A' limits controlled the amount of sulphur dioxide that could be released from the power station in any year and were intended to minimise its impact on the local environment. The 'B' limits controlled the total amount of sulphur dioxide that could be released from all of the coal or oil fired power stations operated by a particular generating company. They were intended to reduce the impact of sulphur dioxide releases on areas sensitive to acid deposition across the country as a whole.

How has electricity generation and supply developed in the UK?

Figure 5.1 shows the fuels used to produce electricity in the UK in 1970, 1980, 1990 and 1996. For example, in 1970, coal and oil produced 88% of the UK's electricity, but by 1996, this had fallen to less than half, with gas producing 21% and nuclear sources generating 28%.

Figure 5.1 Fuel used for electricity generation[1]



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The total amount of electricity produced increased through the 1970's and 1980's but has stabilised since the 1990's. Recognising the need for diverse and sustainable sources of energy and concerned about the implications of a 'dash for gas'; the Government reviewed the possible energy sources used for power generation in its White Paper in October 1998. The White Paper acknowledged the need for coal and oil fired energy sources but highlighted the role of flue gas desulphurisation (FGD) - a treatment process used to reduce sulphur dioxide emissions from coal-fired power stations.

What is flue gas desulphurisation and how does it work?

In conventional power stations the waste gases containing sulphur dioxide, nitrogen oxides and particulate matter produced in the boiler pass through precipitators where almost 99.9% of the particulate matter is removed.

The remaining flue gases containing sulphur dioxide and nitrogen oxides then pass up the chimney where they are dispersed in the atmosphere.

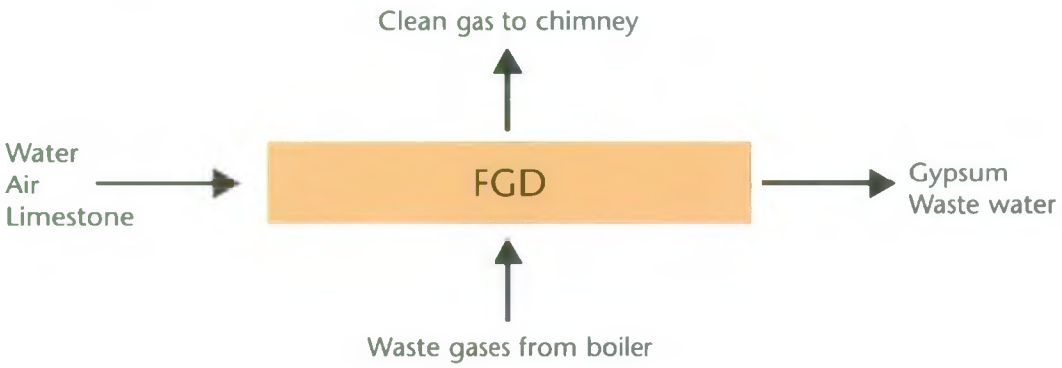
A flue gas desulphurisation plant fitted to the power station between the precipitators and chimney can remove the sulphur dioxide in the flue gas and works by spraying the flue-gas with a mixture of ground limestone and water.

The limestone removes the sulphur dioxide and in the process is converted to gypsum. Once the water has been removed, the gypsum can be sold for use as plasterboard, plaster or cement manufacture. The flue-gases now containing less than 10% of the original sulphur dioxide pass up through the chimney and into the atmosphere.

[1]Source: UK Energy in Brief. Department of Trade and Industry, Government Statistical Service July 1997.

5

Figure 5.2 How FGD works



What flue gas desulphurisation is currently in place?

Only two power stations in England and Wales are currently fitted with FGD; Drax, now owned by the AES Corporation and Powergen's Ratcliffe-on-Soar which together represent approximately 25% of coal and oil fired capacity in England and Wales. However, Eastern Generation has developed plans to fit FGD at West Burton and Edison Mission Energy who now own Ferrybridge and Fiddlers Ferry, are investigating FGD at one or both of these stations. When implemented these changes will result in an increase of 58% in the capacity of power stations in England and Wales fitted with FGD equipment by 2005. Although FGD can be fitted to existing power stations, significantly improving their environmental performance, the cost of doing this can run into several hundred million pounds depending on the size and design of the generating plant. Because the technology is expensive to install and also increases the running costs of the station, it is only cost-effective to install where the station has a long expected lifetime and/or a relatively high level of utilisation.

What Government recommendations were made for the use of flue gas desulphurisation?

The Government's White Paper indicated that each major coal-fired generating company should be encouraged to have at least one FGD-fitted station and that generators should, where practicable, utilise their FGD fitted stations more intensively than their other coal or oil fired stations. Following the recent sale of Drax to AES and that of Eggborough to British Energy, the Agency will be discussing with the companies that do not operate a FGD fitted station the possibility of fitting FGD in accordance with Government policy.

It concluded that whilst continuing to protect the environment, regulation of sulphur dioxide emissions should be flexible to allow generating companies to compete effectively and use fuel sources which contribute to the UK's security of energy supply. To protect the environment, the Government also confirmed that the target set by HMIP to cut sulphur dioxide emissions from the electricity supply industry in England and Wales to 365000 tonnes must be achieved by 2005. In 1997 figures from power stations in England and Wales showed that production was 902000 tonnes, therefore this planned reduction represents a cut of 60% in emissions of sulphur dioxide.

The Agency responded to the Government's policy by revising its previous proposals for controlling pollution from coal and oil-fired power stations as outlined here.

How has the Agency revised the controls placed on individual power stations?

Revised controls on individual power stations ('A' limits)

The Agency has assessed the impact of releases of sulphur dioxide and nitrogen oxides on vegetation and acid sensitive areas near individual power stations. For sulphur dioxide, that is the most significant pollutant, the Agency has also assessed the contribution power stations make against the Government's National Air Quality Objectives. The Agency has revised the 'A' limits and the new controls will:

- Lead to a gradual tightening in station specific limits between now and 2005 for sulphur dioxide, thereby improving the protection provided to sensitive environments arising from the operation of individual power stations;
- Require operators to develop an air quality management plan that will ensure the station meets the Government's National Air Quality Objectives;
- Require operators to develop a programme for monitoring air quality in the area surrounding the station.

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Revised controls on electricity generating companies ('B' limits)

The release of acid gases has a cumulative impact upon the environment throughout the UK. The Agency has re-assessed the impact of sulphur dioxide and nitrogen oxide releases on areas sensitive to acid deposition and also considered the costs of sulphur dioxide reduction for the electricity supply industry in England and Wales.

Following this assessment, the Agency revised its controls to encourage the installation of additional FGD plants and a greater utilisation of existing plants within a commercially competitive environment for operators engaged in electricity production.

The revised Agency controls will:

- Require that by September 2005, the total amount of sulphur dioxide that can be released from the coal and oil fired stations in England and Wales is less than 398 thousand tonnes, (approximately equivalent to 365 thousand tonnes in the calendar year 2005, which, compared to 902 thousand tonnes in 1997 is a reduction of 60%);

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- Require individual operators to run their FGD equipped power stations ahead of non-FGD stations;
- Allow generators who are increasing their share of the electricity generation market, to exceed their B-limit, within strict limits set by the Agency, provided they are operating their plant in an environmentally acceptable manner. This will mean that they are fully meeting the conditions of their authorisation and in addition, are utilising their FGD equipped stations at a level twice that of non-FGD equipped stations. (Operators without FGD equipped stations would not be eligible for this flexibility.);
- Allow controlled flexibility in B-limits in the last two years of construction to companies installing FGD plants. This may lead to some short-term increase in sulphur dioxide emissions between now and 2005 but will see significant reductions in the release of this pollutant in the longer term;
- Limit the amount of SO_2 released per unit of electricity generated to ensure environmentally acceptable operation whilst allowing flexibility in B-limit operation;
- Require all operators of existing FGD plant to submit a case for their upgrading to improve the removal of SO_2.
- Where units are expected to operate above 40% load factor beyond October 2001 the operators will be required to submit a case for fitting FGD. (A power station usually consists of one or more generating units, the load factor is the percentage of the year that the unit is expected to operate);
- Require operators to submit written statements on the expected life and capacity of their generating stations. The expected economic life of a process is a factor for the Agency to consider in deciding whether pollution abatement techniques can be considered excessively costly. If the remaining life of a station is short it will not normally be appropriate to require the fitting of expensive new abatement equipment.

What impact will these new proposals have?

The Government has set national objectives for a number of pollutants including sulphur dioxide and the new controls on power stations will ensure that these are achieved. Once implemented, these proposals will significantly reduce the health and environmental effects of power stations by requiring power stations to ensure they meet national air quality targets by 2005.

In addition to this, modelling studies have shown that currently approximately 3.3 million hectares of UK ecosystems are at risk from acid deposition from natural background, European, domestic and industrial sources. The predicted 60% reduction in sulphur dioxide releases from power stations will reduce this risk area by between 25-35% although this figure will also depend upon the reduction in acid deposition from other sources.

How will this affect the occurrence of future air pollution episodes?

The sulphur dioxide emission reduction programme outlined here is governed by the need to protect particularly sensitive sections of the population such as the elderly and chronic asthma sufferers and also existing environmental ecosystems. The episode investigated in this report was a meteorologically driven event where the emission of sulphur dioxide from large industrial processes, most significantly the coal-fired power stations, was accumulated in the atmosphere before being dispersed. By reducing the overall emission of sulphur dioxide, the size of any potential accumulation will therefore also be reduced thus reducing the frequency and intensity of similar air pollution episodes. The complete eradication of this type of air pollution episode however, can only be accomplished by the complete elimination of sulphur dioxide to air, something that is not considered technically or economically feasible at this point.

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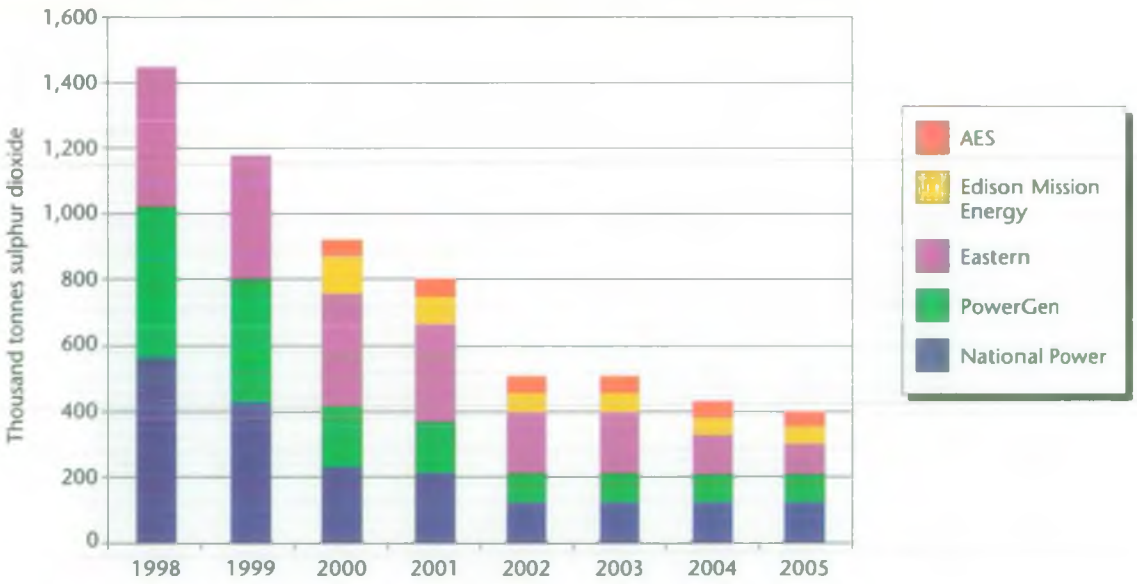
Figure 5.3 Reduction in power station limits for sulphur dioxide through to 2005



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Conclusions

- A serious air pollution episode, caused by sulphur dioxide, occurred across the Midlands and South Yorkshire on September 2nd 1998 which prompted widespread complaint and some media interest.
- The Agency was prepared for the incident and responded appropriately.
- The widespread nature of the incidents indicated a regional-scale air pollution episode was taking place, and that most probably no single regulated process could be culpable.
- Monitoring stations in South Yorkshire and the Midlands recorded peak sulphur dioxide concentrations up to six and a half times higher than the air quality standard; concentrations were high enough for asthmatic individuals to experience adverse effects.
- The incident was driven by the weather occurring on the 1st and 2nd September 1998. A period of low wind speed allowed pollutants from a range of industrial sources to

accumulate in the atmosphere to a high concentration before dispersal.

Numerical modelling of emissions from relevant and potentially culpable industrial processes was carried out using the Met. Office's NAME model. This report shows that NAME performed well in modelling the episode but that the modelling can be improved. The highest sulphur dioxide peak was recorded at the DETR monitoring station in Nottingham where NAME modelled the peak to within a factor of two.

The NAME model also predicted that 95% of the sulphur dioxide detected at Birmingham, Ladybower, Nottingham, and Stoke-on-Trent originated from coal-fired power stations in the Aire and Trent valleys.

The current programme to reduce sulphur dioxide emissions from coal and oil-fired power stations in England and Wales, should reduce the frequency and intensity of this type of air pollution episode in the future.

7 Glossary

This glossary breaks into 3 sections, acronyms, terms, and a short section explaining how time and concentrations have been used in this report.

1. Acronyms

ADMS	Atmospheric Dispersion Modelling System
AERMOD	AMS/EPA Regulatory Model
AEA	Atomic Energy Authority
AEAT	AEA Technology plc
AMS	American Meteorological Society
APHEA	Air Pollution and Health: a European Approach
AQ	Air Quality
AQDD	Air Quality Daughter Directive
AQMA	Air Quality Management Area
AUN	Automatic Urban Network
BAT	Best Available Techniques
BATNEEC	Best Available Techniques Not Entailing Excessive Cost
BST	British Summer Time
CCTV	Closed Circuit TeleVision
CD-ROM	Compact Disc – Read Only Memory
CO	Carbon monoxide
COMEAP	Committee on the Medical Effect of Air Pollutants, reporting to DoH
COPD	Chronic Obstructive Pulmonary Disease
DC	District Council
DETR	Department of the Environment, Transport and Regions
DoE	Department of the Environment, now part of DETR
DoH	Department of Health
EA	Environment Agency
EA95	Environment Act 1995
EPA	Environment Protection Agency (of the USA)
EPA90	Environmental Protection Act 1990
EPAQS	Expert Panel on Air Quality Standards, reporting to DETR
EU	European Union
FEV_1	Volume of air expired during the first second of a maximal or 'forced' expiration
FGD	Flue Gas Desulphurisation
GMT	Greenwich Mean Time
HCs	Hydrocarbons
HMIP	Her Majesty's Inspectorate of Pollution, a predecessor organisation to the Environment Agency
IPC	Integrated Pollution Control
IPPC	Integrated Pollution Prevention and Control
km	kilometre; 1,000 metres
kT	kilotonnes
LA	Local Authority
LAAPC	Local Authority Air Pollution Control
m	metres
MAAPE	Medical Aspects of Air Pollution Episodes
mb	milli-bar units used commonly to measure atmospheric pressure
NAME	Nuclear Accident ModEl

NAQS	UK National Air Quality Strategy 1997
NE	North East
NETCEN	National Environment Technology Centre (part of AEAT)
NOAA	National Oceanographic and Atmospheric Administration (of the USA)
NO	Nitric Oxide, properly called nitrogen monoxide
NO_2	Nitrogen Dioxide
NO_x	Total oxides of nitrogen; conventionally the mixture of NO and NO_2 in the atmosphere.
O_3	Ozone
PAH	Polycyclic Aromatic Hydrocarbons
PM	Particulate Matter
PM_{10}	Particulate Matter (10 µm): term applied to suspended particulate matter with an aerodynamic diameter of less than 10 µm
ppb	parts per billion
PPC	Pollution Prevention and Control
ppm	parts per million
Q-Q	Quantile-Quantile
RCC	Regional Control Centre
SO_2	Sulphur Dioxide
SW	South West
TSP	Total Suspended Particles
UKMO	UK Met. Office
UM	Unified Model
UTC	Universal Time Co-ordinate
WHO	World Health Organisation
µg/m³	Measure of pollutant concentration by the mass of pollutant in a volume of air. Millionths of a gram in a cubic metre of air.
95% CL	95% Confidence Limits; the range of values within which there is a 95% chance of the true result falling

2. Terms

Benzene is a chemical compound, the molecule of which comprises six carbons and six hydrogen atoms. There is evidence that exposure to the substance can cause cancer.

Carbon Monoxide (CO) is a gas produced in the process of combustion. Outdoors, the main sources of CO are vehicle exhausts, and the threat to health is the reduction in the oxygen carrying capacity of the blood.

Flue Gas Desulphurisation is a process that removes sulphur dioxide gas from the waste gases before their release to the atmosphere

Mesoscale is a scale from about 10 to a few hundred km's.

Nitric Oxide (Nitrogen Monoxide) see Nitrogen Dioxide

Nitrogen Dioxide (NO_2) is a gas produced by reaction of nitrogen and oxygen in combustion processes. The reaction usually takes place in two stages, the first resulting in the formation of nitric oxide (NO), this compound then being oxidised over time to produce nitrogen dioxide. Wherever nitrogen dioxide occurs, nitric oxide is also found, and these oxides of nitrogen are know collectively as NO_x. Nitrogen dioxide may have both acute and chronic effects on health, particularly people with asthma.

Objectives, Air Quality air policy targets setting out what the Government and the devolved administrations intend should be achieved in the light of air quality standards. They are generally expressed as a given ambient concentration to be achieved, either without exception or with a permitted number of exceedences, within a specified time-scale.

Ozone is a form of oxygen where three oxygen atoms are combined. It is an irritant to delicate surface tissues of the body.

Occluded Cold Front is an old frontal system where warmer air precedes the front.

Smog a blend of *smoke* and *fog*.

Standards, Air Quality are the concentration of pollutants in the atmosphere which can broadly be taken to achieve a certain environmental quality. The standards relating to the quality of air are based on the assessment of the effects of each pollutant on human health including the effects on sensitive sub-groups.

Sulphur Dioxide (SO_2) is formed by the combination of one atom of sulphur and two atoms of oxygen. At normal temperature and pressure is a gas. It dissolves in water to give an acidic solution. It is an irritant when inhaled, because of its acidic nature and high concentrations may cause breathing difficulties in people exposed to it.

Tephigram is a graphical representation of the observations of pressure, temperature and humidity, made in vertical sounding of the atmosphere.

Universal Time Co-ordinate is the time measurement system used by the Meteorological Office.

1,3-Butadiene is a chemical compound, the molecule of which comprises four carbons and six hydrogen atoms. There is evidence that exposure to the substance can cause cancer.

3. Use of time and concentration

About time

When collected together, the information contained in this report originally used three different time standards:

- the Environment Agency's Regional Control Centre log was in British Summer Time (BST);
- the DETR monitoring data was in Greenwich Mean Time (GMT);
- the information supplied by the Meteorological Office was in Universal Time Co-ordinate (UTC).

In order to unify the presentation of material these times have been converted into GMT. In fact no conversion between GMT and UTC is necessary for the UK, the difference between the two systems is a few thousandths of a second, which has been ignored.

About concentration

The concentration of air pollutants can either be quoted on a mass per volume basis (e.g. µg/m³) or on a volume per volume basis (e.g. ppb). Conversion between these two methods can be accomplished knowing the molecular weight of the pollutant and a reference temperature and pressure. Wherever possible concentrations in this report are quoted on a volume per volume basis and a reference temperature of 20 °C and pressure of 1013 mb have been used.

The conversion by WHO of their 125 µg/m³ air quality guideline for sulphur dioxide is made at 0 °C giving a volume per volume concentration of 44 ppb, whilst when the conversion is made at 20 °C a volume per volume concentration of 47 ppb is calculated.

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www.sat.dundee.ac.uk

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8

9 Acknowledgement

This investigation and report is only possible due to the contribution of many individuals in organisations external and internal to the Environment Agency.

The Environment Agency wishes to thank, in particular, staff at the Met. Office for their work in the air dispersion modelling and reporting section, Mansfield DC for the supply of their monitoring data and the review of the report carried out by Professor Roy Harrison of Birmingham University.

The Environment Agency has also made full use of publicly available information on web sites operated by, or on behalf of, the Department of Health, the Department of the Environment, Transport and Regions and Dundee University.

The Environment Agency wishes to thank the Stationery Office for their kind permission to reproduce the extracts of the COMEAP and EPAQS Reports.

The Environment Agency wishes to thank those who contributed to the production of this report, in particular, Charlesworth Communications, Simon Derry Photography, Whitehouse Mainwaring Design and Heron Press.

Photograph of Nottingham provided courtesy of Profile Nottingham.

Finally, the Agency would like thank its many staff who helped obtain the emission data from the sources modelled.

Annex I
'Classic' air pollution episodes

Introduction

Air pollution episodes are influenced by:

- The source of the pollutants;
- The meteorological conditions.

The timing of the emissions also has a role to play. For instance, traffic emissions are characterised by two diurnal peaks corresponding to morning and evening rush hours that may influence the occurrence of an episode. Episodes due to unplanned releases from industrial processes could occur at any time and continuous industrial processes may contribute at times when other, diurnally varying, sources are insignificant.

Source characteristics

In terms of sources there are two main types:

- Area sources (e.g. domestic, urban traffic);
- Point sources (e.g. industrial chimneys).

Most monitoring sites tend to be in city centres, therefore surrounded by sources and so will measure local pollution whatever the wind direction. These emissions are also at ground level hence they manifest below low-level temperature inversions. Conversely, emissions from point sources are usually at some height above the ground, and potentially above low-level inversions. These emissions only impact on monitoring sites when a suitable wind direction exists.

Meteorology

The role of *wind direction* has been mentioned, but *wind speed* is also important. For emissions at ground level, higher wind speeds cause greater dilution. They also tend to be associated with greater turbulence and hence improved dispersion resulting in lower concentrations.

The influence of wind speed is not as straightforward for elevated point sources. Increasing wind speed reduces the ability of a plume to rise through the atmosphere. The plume becomes bowed or 'bent-over' reaching ground level earlier, although the increasing wind speed also serves to dilute the pollutants and improve dispersion.

A stable atmosphere means reduced vertical air motion and therefore reduction of turbulent dispersion of pollutant emissions. This *atmospheric stability* facilitates air pollution episodes caused by low-level emissions. *Atmospheric instability* has the opposite effect causing strong vertical motion and pollutant dispersion, and pushing plumes down to ground level close to source.

Temperature normally falls with increased height above the earth's surface. A *temperature inversion layer* is characterised by an increase in temperature with height. When this occurs, the inversion effectively traps pollutants below it, in the area between the ground and the inversion. This area is called the mixing layer or boundary layer and is very important as it contains the air we breathe. Particularly large thermally buoyant plumes can fully or partially penetrate an inversion.

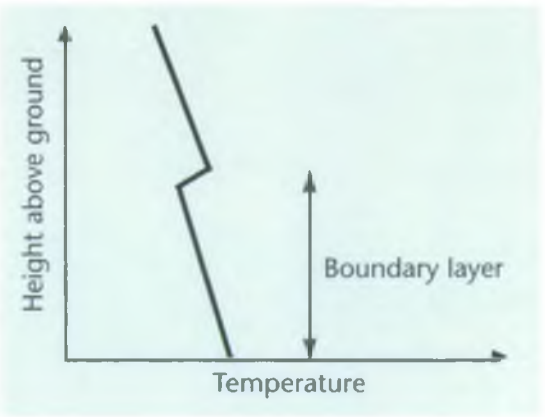
AI

There are three basic types of inversion:

- *Radiation inversion* due to cooling at the ground;
- *Subsidence inversion* at high level under a high pressure weather system;
- *Advection inversion,* due to cold air moving in above warm, or warm air in above cold, these are not very common.

Episodes caused by area source of pollution, low-wind speed and temperature inversions are generally a regional phenomenon, and can affect several monitoring stations at the same time. Point source episodes are generally more localised, sometimes impacting on just one monitoring station.

Figure A1.1 Temperature inversion defines boundary layer top



Classic episodes

It is possible to identify three common types of episode relating to primary emissions:

Table A1.1 Common types of episode

TYPE	DESCRIPTION
A1	A plume from a point source reaching the ground during periods of unstable atmospheric conditions. A daytime occurrence, associated with light-moderate wind speeds and most frequent in the summer.
A2	A plume from a point source reaching the ground during periods of neutral or slightly unstable atmospheric conditions. Associated with moderate-strong winds.
A3	Plume from a point source being trapped above the boundary by a low-level temperature inversion. As the inversion breaks up, the plume is mixed down to ground level.
A4	Plumes from a number of point sources dispersing over a wide area during a period of light wind speed and restricted dispersion.
B1	Build up beneath an over-night radiation inversion, associated with low wind speeds.
B2	Build-up over several days beneath a persistent inversion - an extended version of B1. Often associated with poor visibility.
C	Episode related to limited dilution/dispersion from a particular source, e.g. emissions from traffic during periods of light wind speed

Episodes from point sources, especially those regulated by the Environment Agency, are most commonly of type A1, A2, A3 and A4. These are characterised by:

Table A1.2 Common types of episode

TYPE	CHARACTERISTIC
A1	• Normally occur during summer, typically on warm sunny afternoons; • Wind speeds light, and hence, wind direction likely to be variable. Source may therefore not be located upwind of the measurement point; • Episode is likely to arise in immediate vicinity of the source, due to low wind speeds limiting transport of material, and strong vertical mixing leading to rapid decrease in ground level concentrations.
A2	• May occur at any time of year and any time of day; • Wind direction is likely to be steady over time period of 1 hour or more. Source is therefore likely to be located upwind of the measurement point; • Episode is likely to arise in the vicinity of the source, due to relatively high wind speeds encouraging dispersion.
A3	• Normally occurs soon after dawn on cold winter days; • Episode may arise at a considerable distance from the source, due to possibility of substances remaining trapped above the boundary layer for long periods • The upper level wind direction may not be well represented by ground-level data. The source may therefore not be located upwind of the measurement point.
A4	• Can occur at any time of year, but more prevalent during winter months; • Wind speeds light to moderate, and hence wind trajectory likely to be curved. Source may not be located upwind of the measurement point(s); • Episode is likely to arise across a wide regional area; • Episodes are likely to occur sequentially at affected stations, as the polluted air mass moves downwind; • Episode may last several hours at the affected stations as polluted air mass moves across the station.

September 2nd 1998

The Agency has identified this air pollution episode as an A4 episode and it is a classic example of this type.

Annex II
Environment Agency Episode Analysis Protocol

Introduction

The Agency has a common Episode Analysis Protocol used throughout the Agency regions that provides a systematic mechanism for the assessment of an episode's significance by Inspectors. It offers a nationally consistent approach to episode analysis without being unduly prescriptive.

In this annex the Protocol is outlined and the three stages of analysis explained, with reference to the investigated episode on September 2nd 1998.

AII

Stage I Analysis

Notification of an air pollution episode is received by the Agency. The data supplied will consist of DETR monitoring results and key meteorological data. This data is assessed at Stage 1 Analysis in order to rapidly filter out non-relevant episodes and decide whether a more detailed analysis i.e., (Stage II) is required.

At this stage the protocol relies on five questions to establish whether Stage II Analysis is either:

- Definitely required;
- Definitely not required.

Table A2.1 Questions asked on notification

DECISION	QUESTION
Data Validity	Is the episode notification likely to result from invalid data?
Data Values	Do the measured values (in terms of pollutant level and/or episode duration) indicate that the episode is significant? Is the episode likely to be attributable to traffic or other dispersed sources?
Episode History	Have the Agency regulated processes been found to contribute significantly to previous episodes recorded at the monitoring station?
Process Location	Does the wind direction and the location of Agency regulated processes suggest any possible sources?
Regional	Are there other Regional factors which affect the assessment? (Such as notifications in other Agency Regions, or other major sources of pollution are known to exist.)

The decision to proceed to Stage II is discretionary and a further set of four criteria is used to clarify the decision-making process as shown in Table A2.2.

Table A2.2 Questions asked to proceed to stage II analysis

DECISION	QUESTION
Outcome	Is the Stage 1 outcome towards the 'required' or 'not required' ends of the discretionary band?
Data Values	Is low confidence in the wind direction during the episode because wind speed was low and/or wind direction was highly variable? This may suggest that processes not directly upwind may be culpable.
External factors	Was there public and/or media interest in the episode?
Process location	Is the source known with some confidence?

Stage II Analysis

The Stage II tasks identify potential sources of air pollution including individual Agency regulated processes that may have significantly contributed to the episode. If it appears unlikely that an Agency regulated process will have made a significant contribution, and then the purpose is to identify a likely alternative cause.

AII

Stage II Analysis is achieved through:

- Identification of potential Agency regulated processes, if any;
- Obtaining information from operators of potential sources of pollution. The data obtained will be for the period covering a few hours before, to a few hours after the episode and will cover such things as:
  - Release rates for the measured substances (including but not restricted to the substances giving rise to the episode notification)
  - Other information on release conditions (such as temperature, stack exit velocity, stack diameter and height);
  - Whether there were any unusual operating circumstances;
  - Any other fact or anecdotal information that may make analysis of the episode easier.
- A simple statement to describe the episode:
  - Date/time/station/exposure statistics;
  - Significance;
  - Likely sources;
  - Action planned or being taken.
- Decision on whether Stage III (detailed modelling) is required.

The majority of episodes arise from unusual meteorological conditions rather than from unusually high emission rates. Stage II analysis allows the Agency to determine the significance of the episode and whether or not Agency regulated processes will have contributed to it. If the episode is significant and further investigation is required, then Stage III Analysis - Detailed Modelling will be commenced.

Stage III Analysis

Stage III Analysis uses detailed techniques to explore the episode more thoroughly. The analysis carried out is determined by the nature of the information required and of the episode itself and is therefore not prescriptive. Stage III Analysis is most likely to cover the following areas of investigation:

- **Identifying an unknown source**
  Completed when there is no Agency regulated process upwind, or modelling suggests that no single Agency regulated process can be the cause of the entire episode.
- **Detailed study of plume trajectories**
  Particularly suitable during periods of light winds, widespread regional episodes covering a period of several hours, and/or where localised wind flows may be significant (such as land-sea breezes). The Met. Office can generate back trajectories for airflow - i.e. they can predict where the air mass containing the pollutants has come from. This enables identification of likely sources where there are several in the general upwind direction.
- **Modelling of the emission sources**
  Completed using conventional Gaussian models, such as ADMS or AERMOD, or using the Met. Office's NAME model.

The outcome of the Stage III Analysis will normally be a report reflecting the nature and scale of the episode in terms of its duration or the area affected and the exposure of the public to health risks resulting.

Annex III
SO_2 monitoring charts

This Annex contains the 15-minute mean sulphur dioxide monitoring station data for September 2nd 1998 from a selection of monitoring stations. These 22 figures are all scaled to 0-700 ppb (the highest peak was about 650 ppb and occurred in Nottingham) to make the charts visually comparable. Stations not included are those substantially flat during the day (Bolton, Bradford, Cardiff, Exeter, Leeds, Oxford, Narbeth, Plymouth, Port Talbot, Scunthorpe, Sunderland and Swansea) and those that failed during the day (Coventry, Leamington Spa, Norwich, Reading and Rotherham). The charts and underlying data for all of these stations are included on the CD-ROM.

This series of charts is followed by 5 figures that cover the two day period 2nd and 3rd September 1998 for monitoring stations in southern and south-west England and south Wales.

AIII

Figure A3.1 DETR Barnsley 12

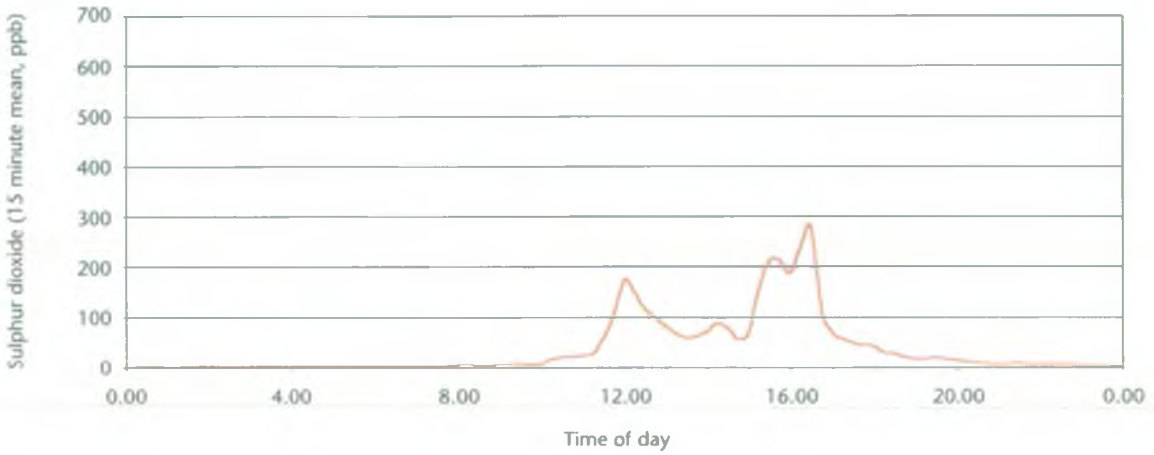


Figure A3.2 DETR Barnsley Gawber

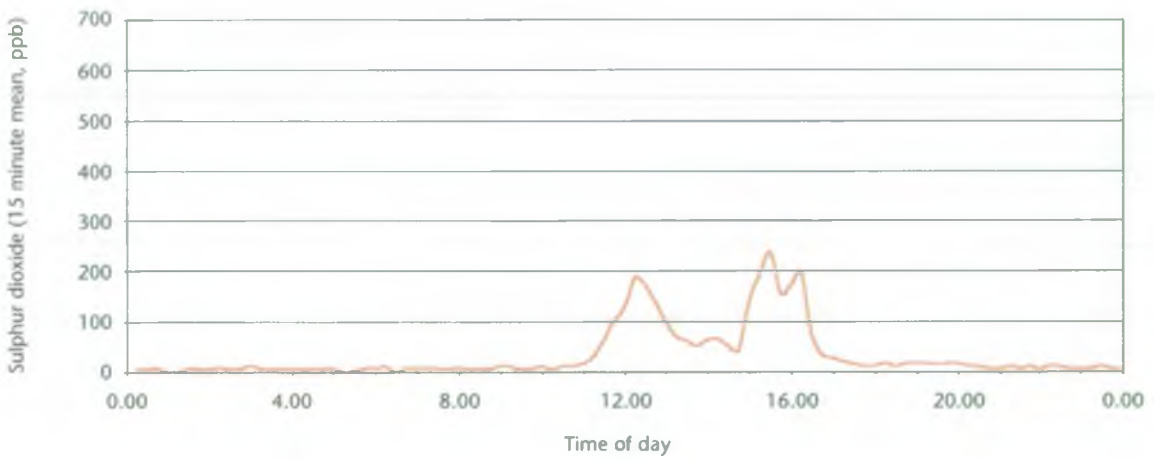


Figure A3.3 DETR Birmingham Centre

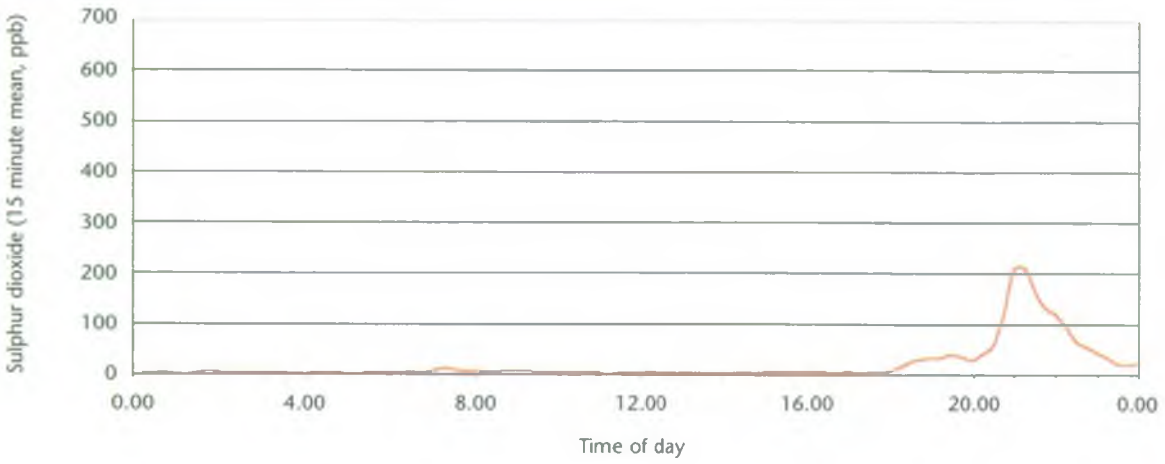


Figure A3.4 DETR Birmingham East

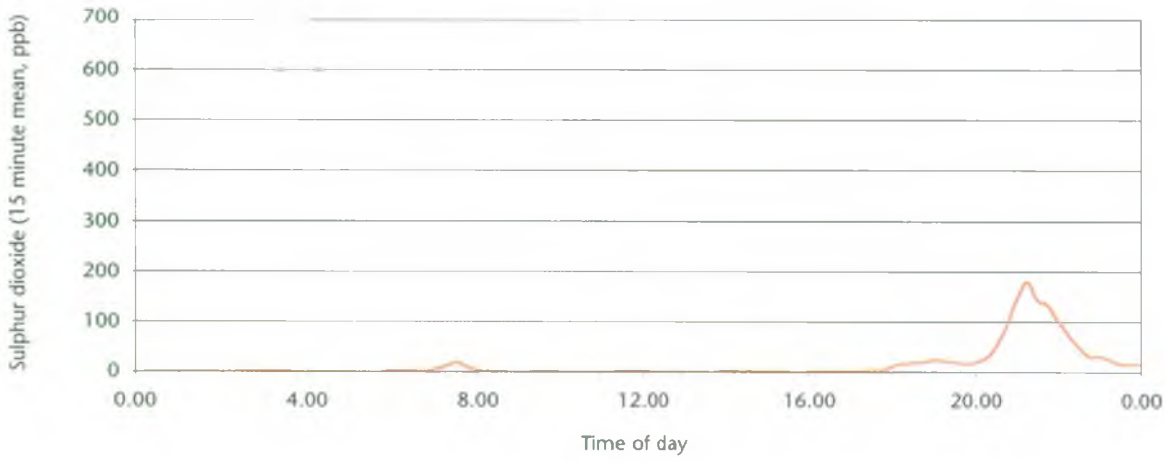


Figure A3.5 DETR Bury Roadside

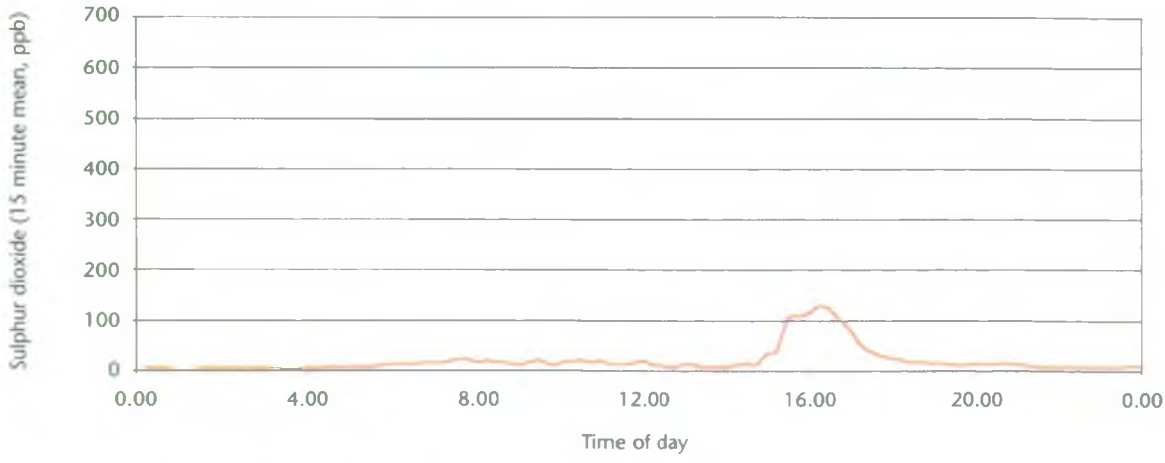


Figure A3.6 DETR Hull Centre

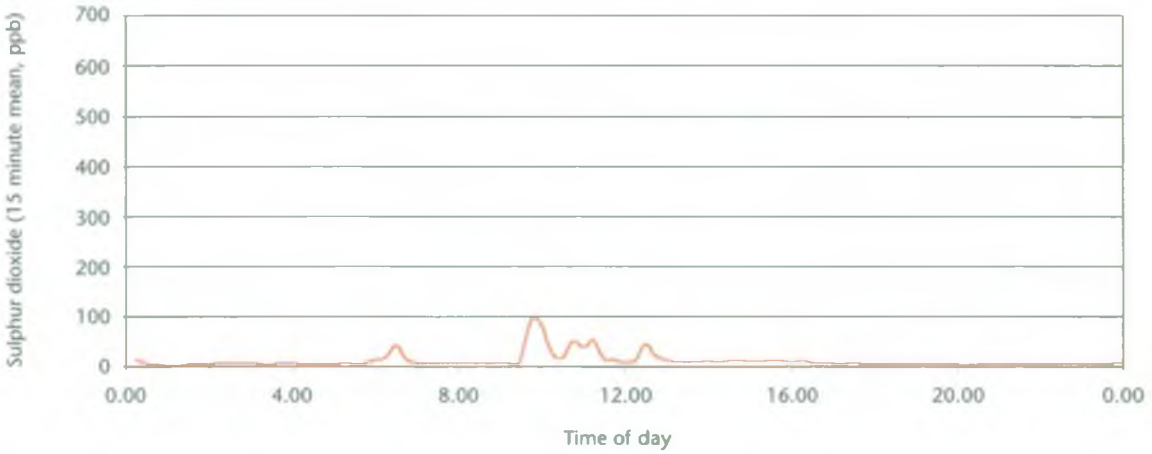


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Figure A3.7 DETR Ladybower

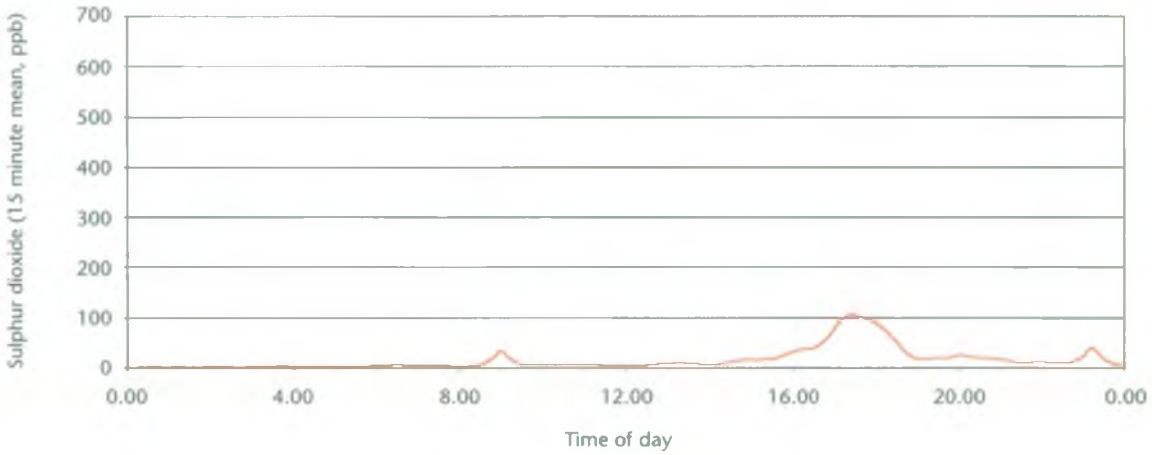

Figure A3.8 DETR Leicester Centre

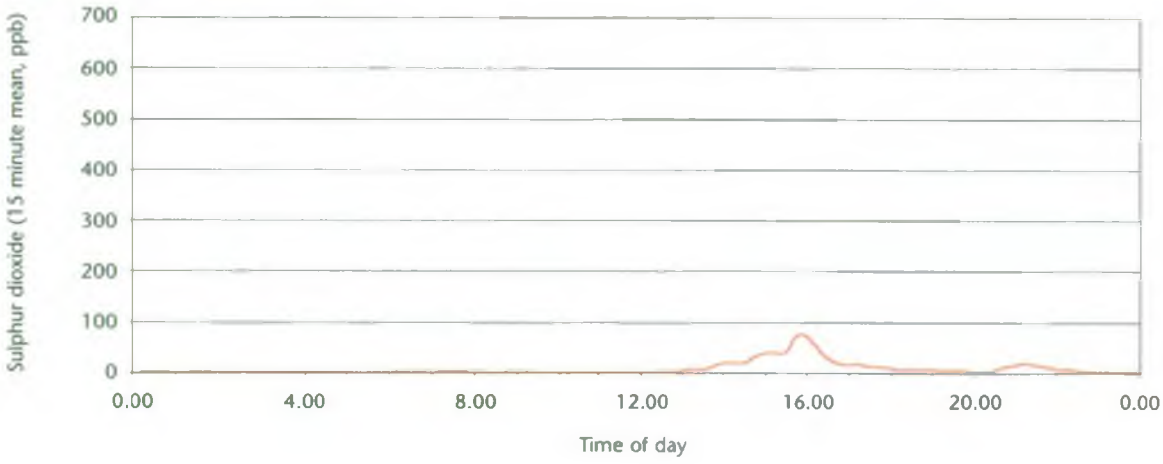

Figure A3.9 DETR Liverpool

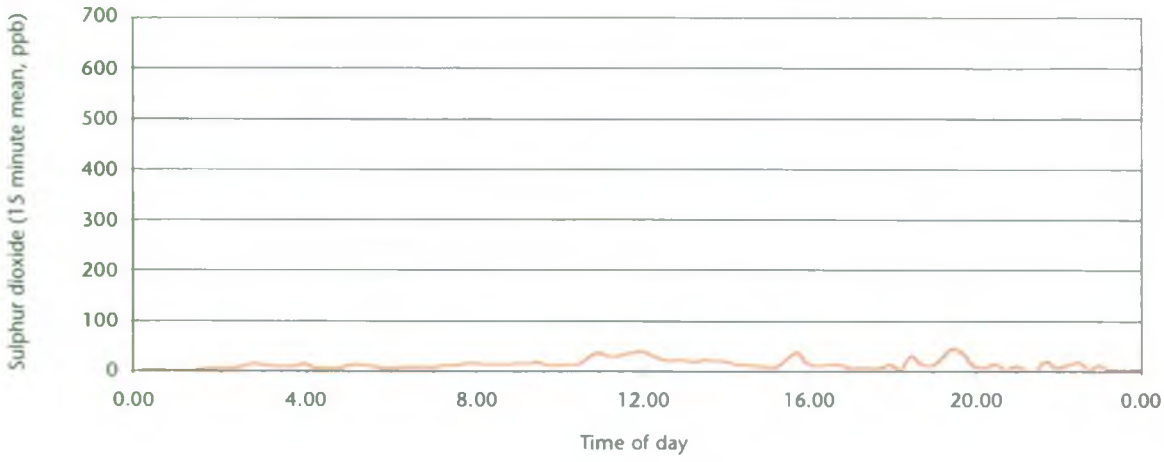

Figure A3.10 DETR Manchester South

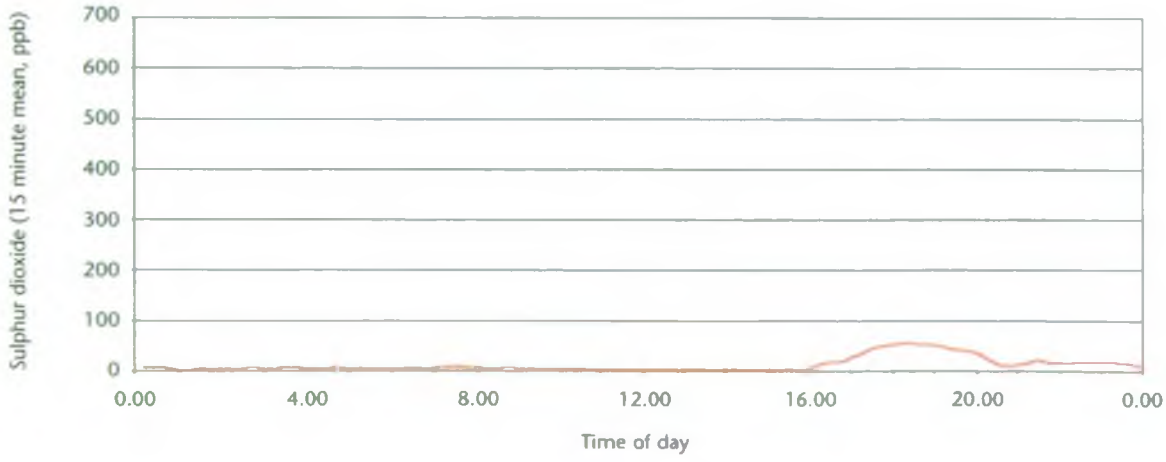

Figure A3.11 Mansfield DC

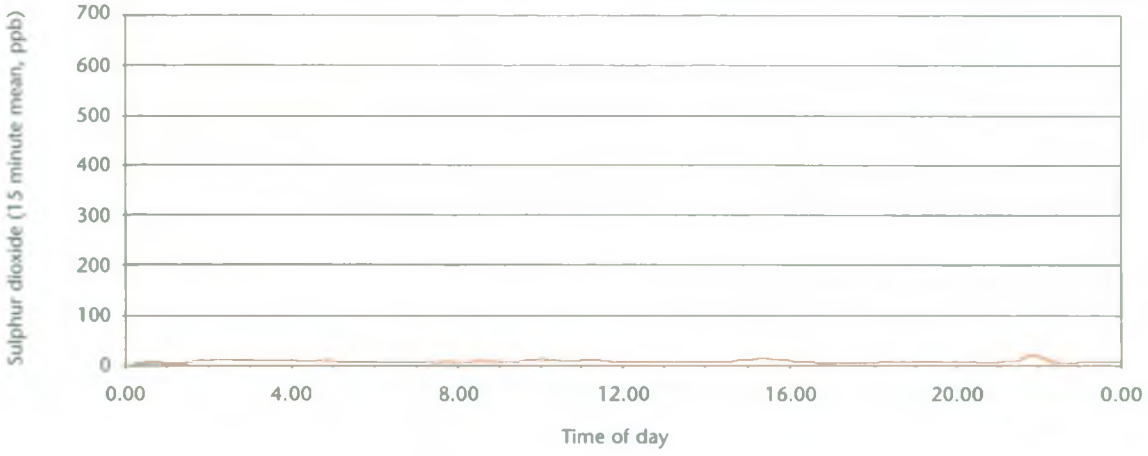

Figure A3.12 DETR Middlesbrough

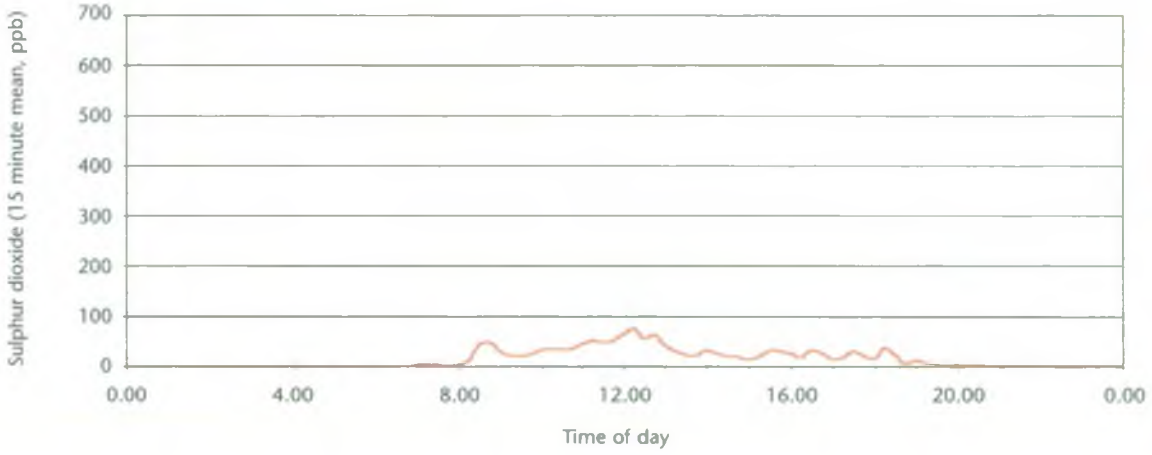

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Figure A3.13 DETR Nottingham Centre

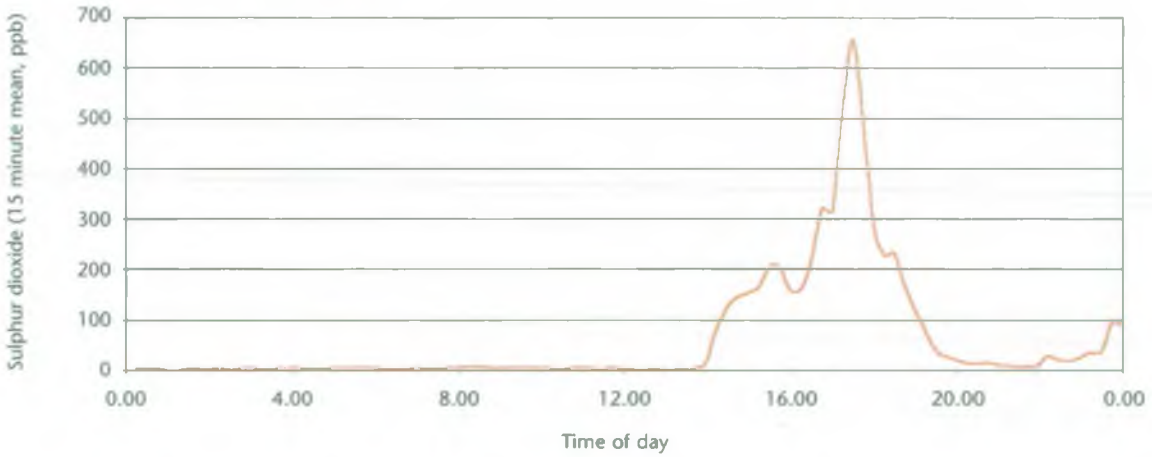

Figure A3.14 DETR Redcar

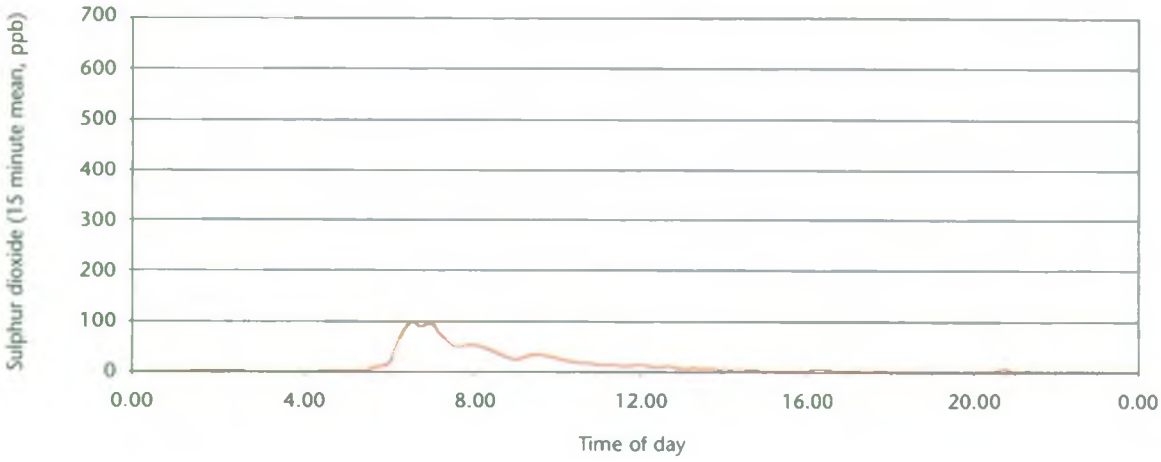

Figure A3.15 DETR Salford Eccles

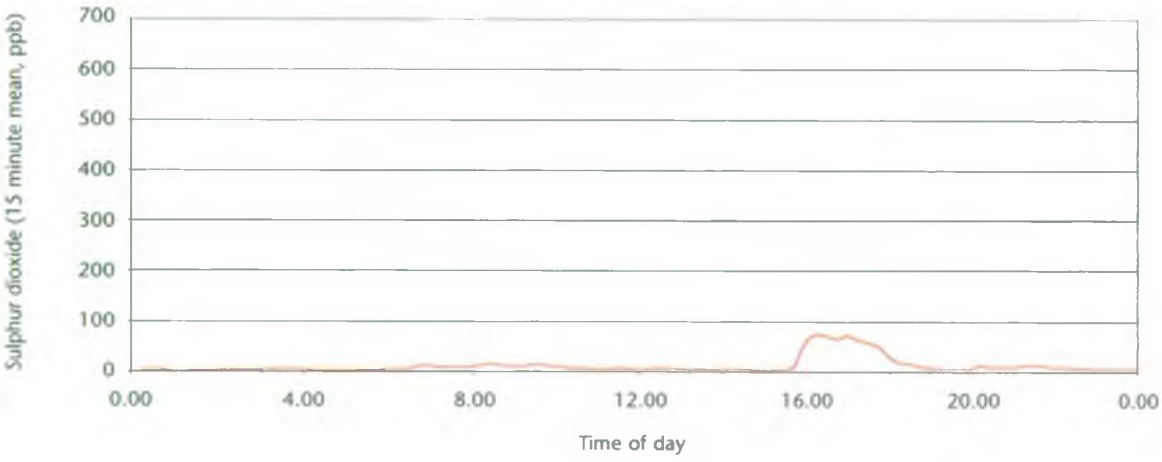

Figure A3.16 DETR Sandwell Oldbury

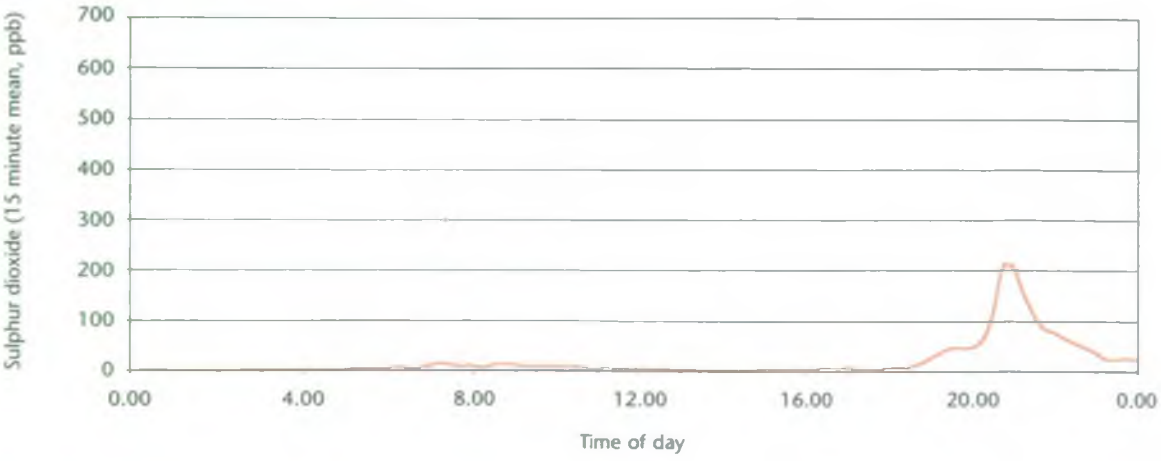

Figure A3.17 DETR Scunthorpe

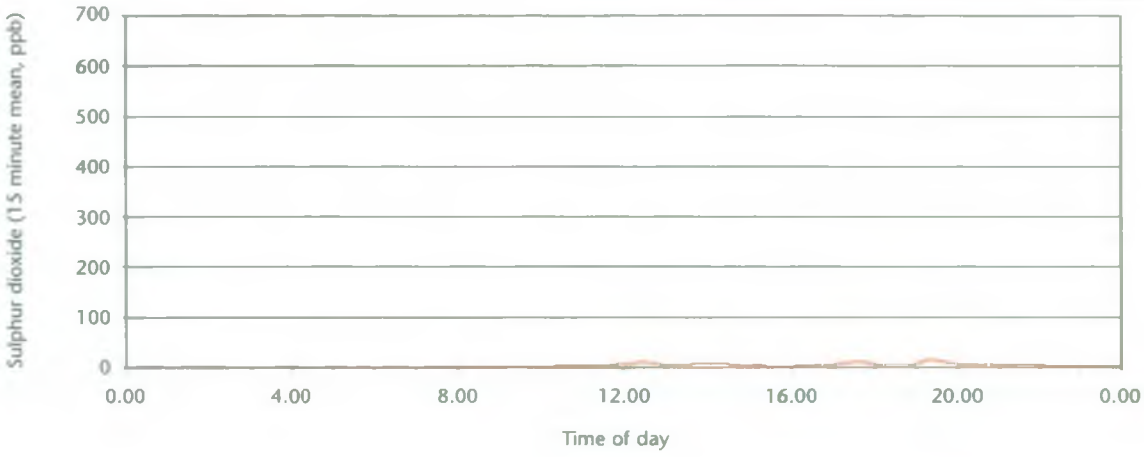

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Figure A3.18 DETR Sheffield

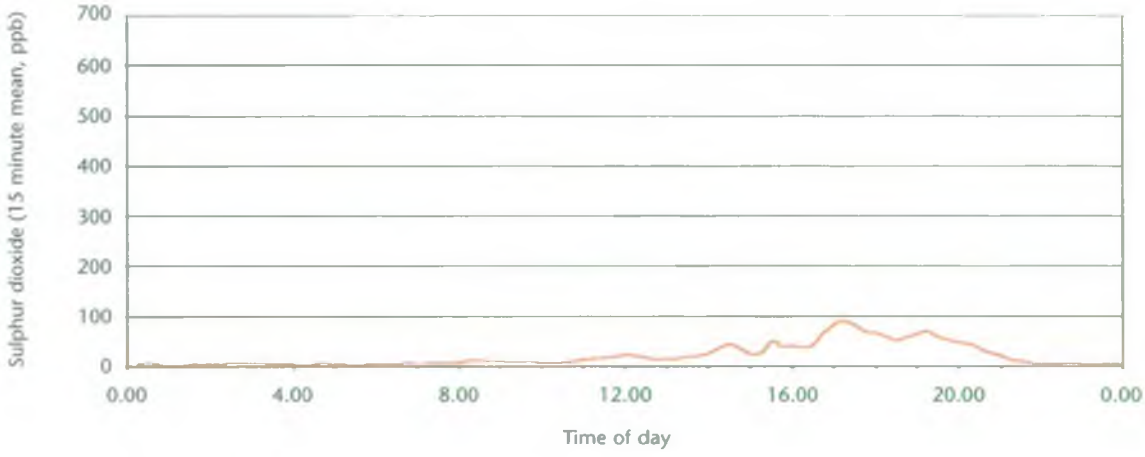


Figure A3.19 DETR Stockport

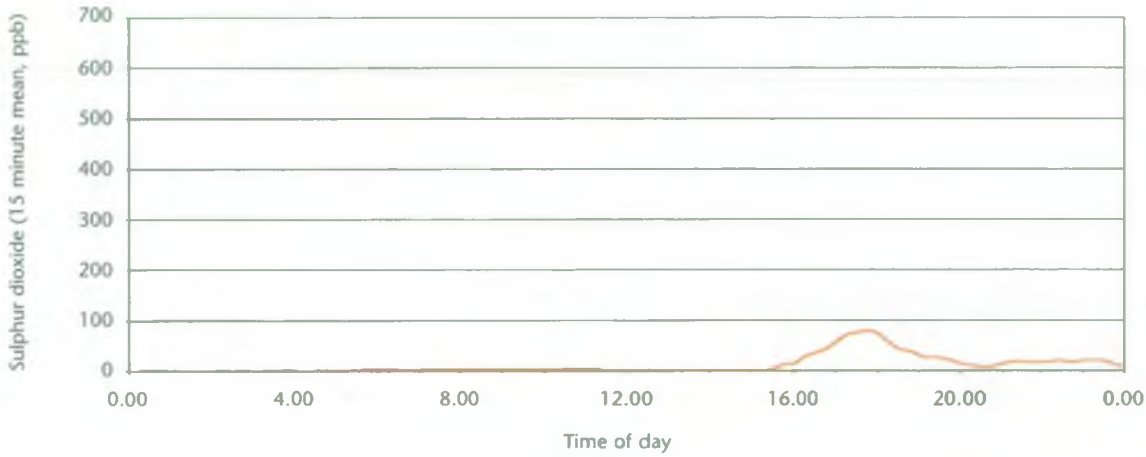


Figure A3.20 DETR Stoke-on-Trent

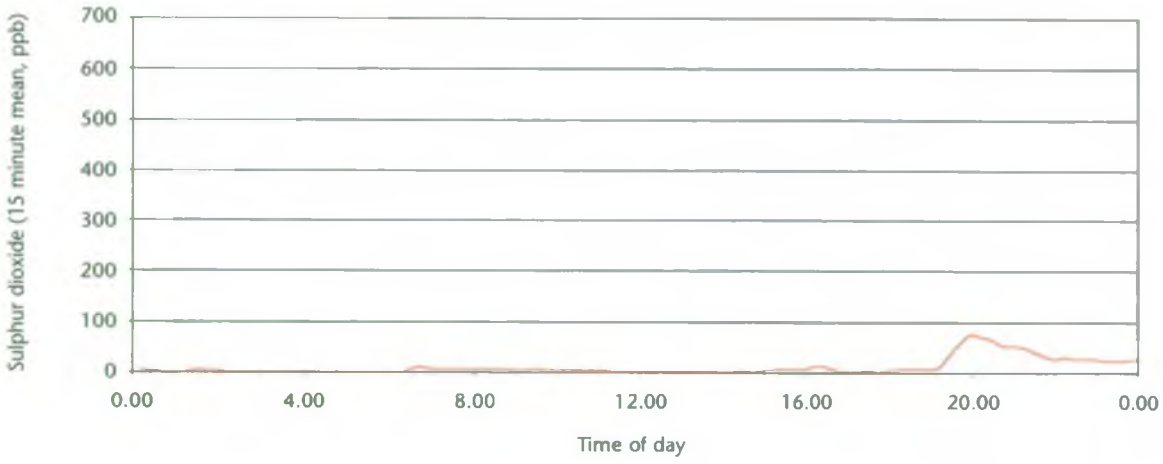


Figure A3.21 DETR Thurrock

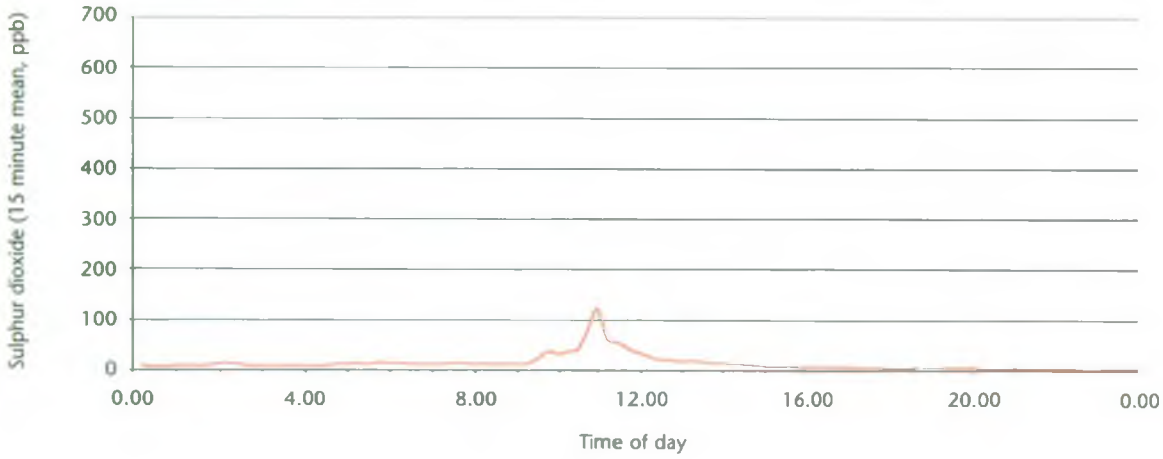
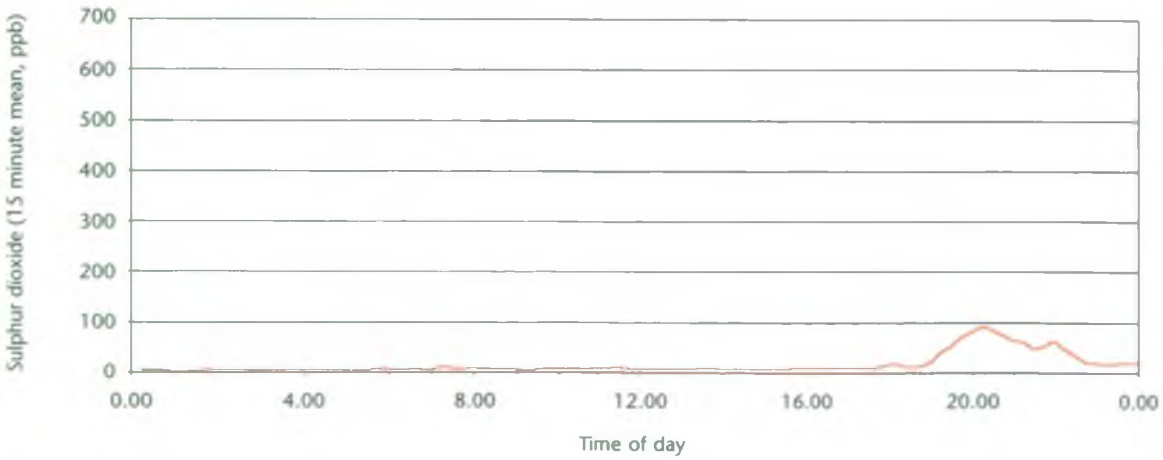


Figure A3.22 DETR Wolverhampton



The following five figures show the 15-minute mean sulphur dioxide concentration at DETR monitoring stations in roughly the south-west quadrant from the study area for both the 2nd and 3rd September 1998. Note that the vertical scale has changed from 0-700 ppb to 0-100 ppb.

Figure A3.23 DETR Bristol

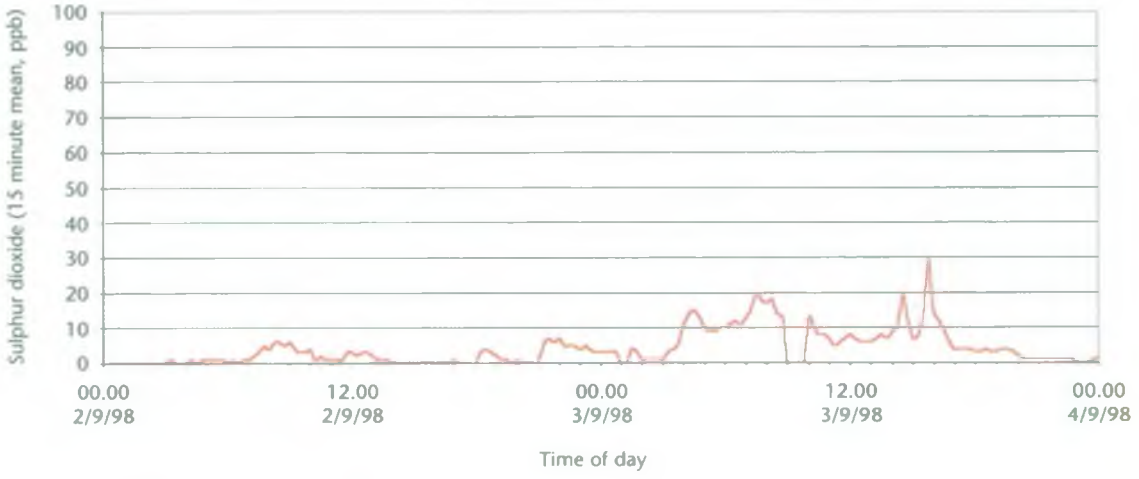


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Figure A3.24 DETR Cardiff

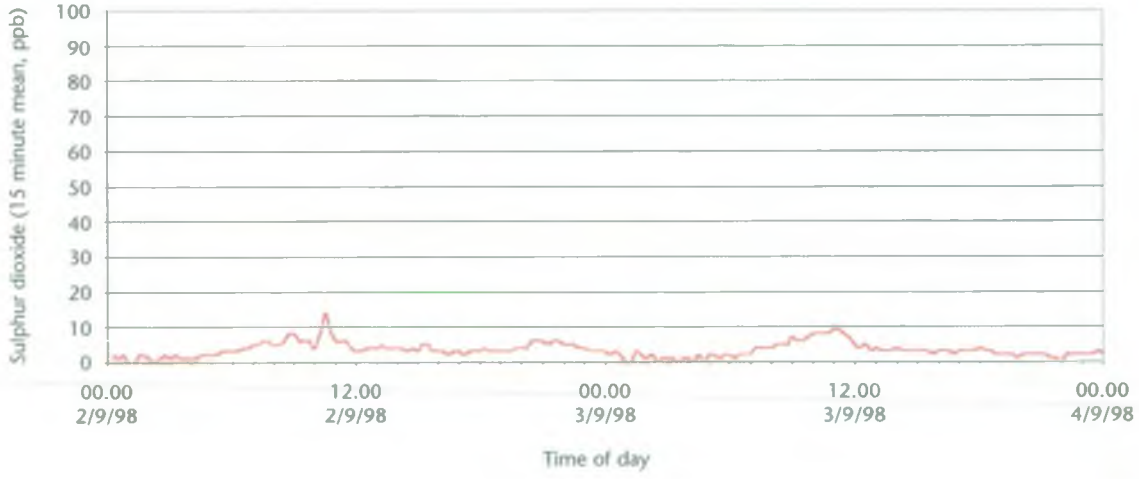


Figure A3.25 DETR Exeter Roadside

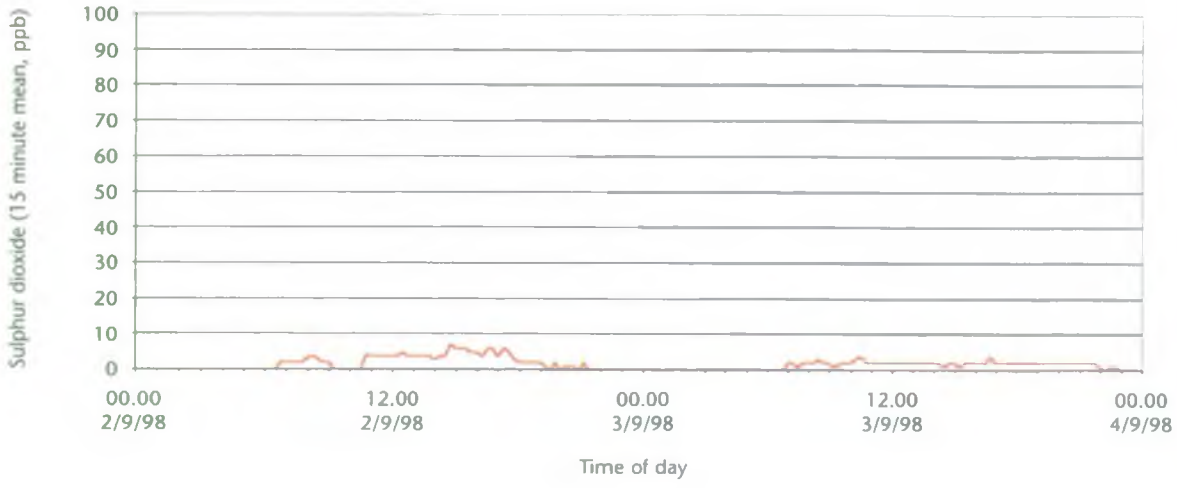


Figure A3.26 DETR Narbeth

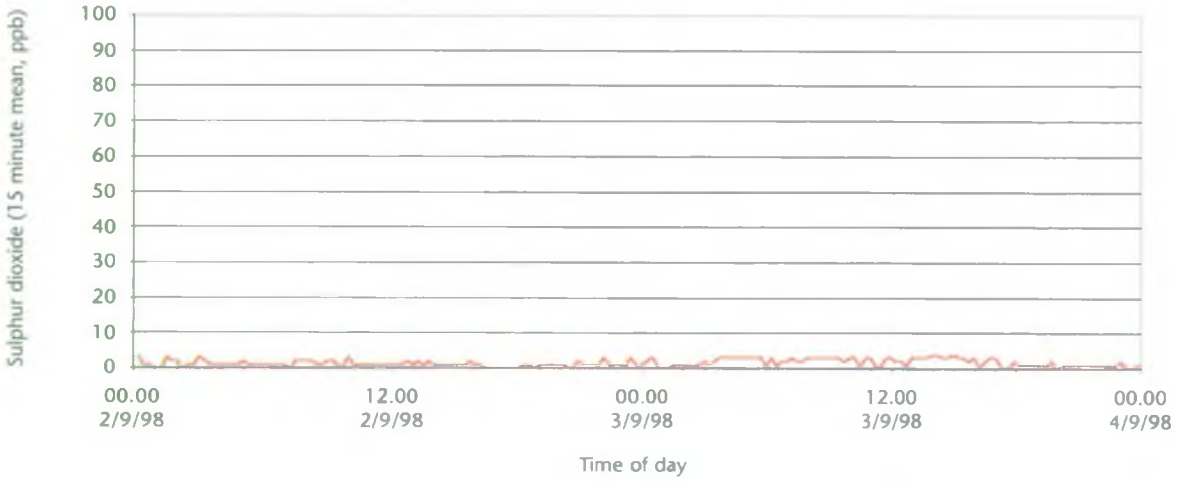
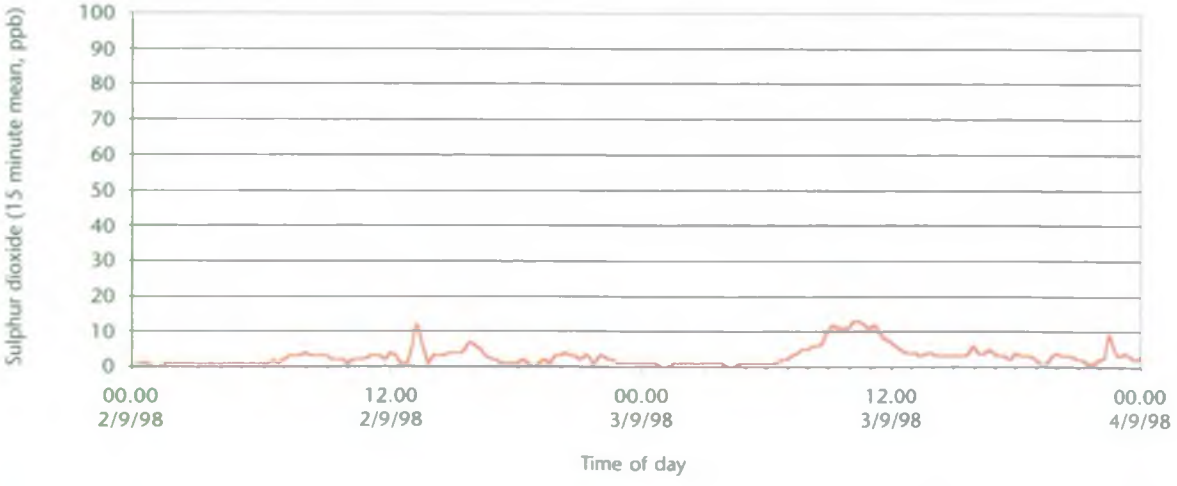


Figure A3.27 Southampton



Annex IV
Sulphur dioxide air quality standards, objectives and banding

AIV

This Annex provides background information for Section 3. It examines the health effects of ambient sulphur dioxide and how these have been translated into air quality standards and objectives under the Government's National Air Quality Strategy (NAQS). The Annex also examines other reports on the health effects of exposure to ambient sulphur dioxide.

Health effects of sulphur dioxide

Sulphur dioxide stimulates nerves in the lining of the nose, throat and the lung's airways. This causes irritation of these areas, a reflex cough, a feeling of chest tightness, and may lead to a narrowing of the airways. The adverse effects of sulphur dioxide on lung function are far more evident in people suffering from asthma and chronic lung disease, whose airways are often chronically inflamed and sensitive. Long-term asthma and lung disease sufferers, particularly those with severe disease, or who are subject to frequent attacks, already have narrowed airways. Any further narrowing due to the presence of excessive sulphur dioxide will significantly increase resistance to airflow in their airways and therefore they experience marked breathing difficulty.

Around 4% of the population of the UK (and a higher proportion among children) suffer with some form of asthma and this figure is rising. Chronic lung disease due to smoking is also common among older people. The air quality standard for sulphur dioxide must therefore take into account the health effects of sulphur dioxide pollution on these particularly vulnerable sections of the population.

Setting air quality standards and air quality objectives

By their nature, set air quality standards cannot be precise. A level can however be defined which if met, will avoid significant risk to health. A standard of this type is essential and practical in order to meet the statutory requirement to render pollution harmless. Such standards must be based on the best available medical and scientific knowledge and understanding.

Air quality standards are set purely with regard to scientific and medical evidence on the effects of a particular pollutant on man or the environment, however, *air quality objectives* take other issues into consideration such as economic efficiency, practicability, technical feasibility and time-scale.

Air quality standards and objectives for sulphur dioxide

In 1991, the Government established an Expert Panel on Air Quality Standards (EPAQS). The panel consists of independent experts appointed for their medical and scientific expertise. Since its creation, EPAQS has made recommendations for a number of air pollutants (1,3 butadiene, benzene, carbon monoxide, nitrogen dioxide, fine particulates (PM_{10}), lead and ozone) which the Government has accepted. More recently, EPAQS has produced a standard for Polycyclic Aromatic Hydrocarbons (PAHs), which is still under review by the Government. Additionally, there are EU limit values, these are generally derived from World Health Organisation (WHO) guideline values. The following panel sets out the detailed WHO guidelines for sulphur dioxide:

EPAQS

Recommendation for an air quality standard for sulphur dioxide

27. The panel recommends an air quality standard for sulphur dioxide in the United Kingdom of 100 ppb, measured over a 15-minute averaging period.
28. This recommendation is intended to reduce the exposure of the population, including individuals who may be particularly susceptible, to levels of sulphur dioxide at which harmful effects are unlikely to occur. Although the exposure studies discussed earlier [in the EPAQS report] have primarily investigated the effect of sulphur dioxide on people suffering from asthma, it is likely that similar effects may be observed in patients with other chronic lung diseases. It is intended that techniques for monitoring the standard be consistent with those of the Department of the Environment's national sulphur dioxide monitoring networks.

Table A4.1 EPAQS air quality standard for sulphur dioxide

POLLUTANT	CONCENTRATION	MEASURED AS
sulphur dioxide	100 ppb	15 minute mean

Additionally, there are EU limit values, these are generally derived from World Health Organisation (WHO) guideline values. The following panel sets out the detailed WHO guidelines for sulphur dioxide:

WHO air quality guidelines for Europe 1987 guideline

It appears reasonable to apply a protection factor of 2 for the protection of public health; a guideline value of 500 µg/m3 [188 ppb] (10 minutes, not to be exceeded) is recommended. A 1-hour maximum that conforms to this guideline can be calculated as approximately 350 µg/m3 [132 ppb].

1994 update and revision

Short-period exposures

The conclusion by WHO reached in 1987 was that the effects of clinical significance became evident in experimental exposure studies, of about 10 min duration, involving exercising asthmatic patients, at concentrations of SO_2 from about 1000 µg/m³ (0.35 ppm) upwards. In deriving a guideline value, an uncertainty factor of two was introduced to allow for the possibility that the most sensitive people may not have been tested. Further studies since then that have included subjects with severe asthma support this conclusion, and it is recommended that a value of 500 µg/m³ (0.175 ppm) should not be exceeded over averaging periods of 10 min. Because exposure to sharp peaks depends on the nature of local sources, no single factor can be applied to this estimate corresponding values over somewhat longer periods, such as an hour.

Exposures over 24 hour periods

Day-to-day changes in mortality, morbidity, or lung function relate to 24-h average concentrations of SO_2 are necessarily based on epidemiological studies in which people are in general exposed to a mixture of pollutants, and guideline values for SO_2 have previously been linked with corresponding values for PM. This approach led to a previous guideline value of 125 µg/m³ (0.04[4] ppm) 24-h average for SO_2, after applying an uncertainty factor of two to the lowest-observed-adverse-effect-level. In more recent studies, the indications are that adverse effects relate more to the particulate component of the mixture than to SO_2, and it is recommended that retaining the 125 µg/m³ (0.044 ppm) [44 ppb] SO_2 guideline with a 24-h averaging period will continue to be protective of public health.

Table A4.2 WHO air quality guidelines for sulphur dioxide

POLLUTANT	GUIDELINE LEVEL	
	CONCENTRATION	MEASURED AS
Sulphur dioxide	188 ppb 47 ppb 19 ppb	10 minute mean 24 hour mean annual mean

Note that WHO use different conditions to convert the 125 µg/m³ air concentration to ppm. They convert the concentration to 44 ppb (0.044 ppm), whereas the conversion used in the UK produces 47 ppb.

And the EU Limit values are:

Table A4.3 EU Air Quality Daughter Directive limit values for the protection of health

POLLUTANT	LIMIT VALUE		DATE TO BE ACHIEVED BY
	CONCENTRATION	MEASURED AS	
Sulphur dioxide	350 µg/m³ not to be exceeded more than 24 times a year	1 hour mean	1 January 2005
	125 µg/m³ not to be exceeded more than 3 times a year	24 hour mean	1 January 2005

AIV

Air quality objectives for sulphur dioxide

Table A4.4 sets out the air quality objectives to be included in regulations for the purposes of Local Air Quality Management (LAQM) for sulphur dioxide:

Table A4.4 Air quality objectives for sulphur dioxide

POLLUTANT	OBJECTIVE		DATE TO BE ACHIEVED BY
	CONCENTRATION*	MEASURED AS	
Sulphur dioxide	132 ppb not to be exceeded more than 24 times a year	1 hour mean	31 December 2004
	47 ppb not to be exceeded more than 3 times a year	24 hour mean	31 December 2004
	100 ppb not to be exceeded more than 35 times a year	15 minute mean	31 December 2004

* Concentrations are specified in µg/m³ with conversion to ppb and ppm

Banding for sulphur dioxide

In order to make air quality information more meaningful, a set of criteria is used to classify air pollution levels into bands, with a description associated with each band. The set of bands for sulphur dioxide is given in Table A4.5.

The pollutant concentrations for each band are set with reference to what is known about the health effects of each pollutant. The first threshold, called the 'standard threshold' is defined by the UK National Air Quality Standard. The second and third thresholds are the 'information' and 'alert' levels that are in line with EC Air Quality Daughter Directive values.

Table A4.5 Banding of concentrations for sulphur dioxide

DESCRIPTION	SULPHUR DIOXIDE (PPB, 15 MINUTE MEAN)	D O H STATEMENT:
LOW	< 100	At these concentrations, it is most unlikely that anyone, even those suffering from asthma would experience any adverse effects. The figure of 100 ppb thus includes a safety margin.
Standard		
MODERATE	100 - 200	There is little evidence to suggest that those suffering from asthma would be significantly affected by exposure to concentrations of sulphur dioxide of less than 200 ppb. This figure was accepted by EPAQS as the lowest level at which clear though rather small effects had been described.
Information		
HIGH	200 - 400	The World Health Organisation has suggested that exposure to 400 pbb sulphur dioxide may lead to significant narrowing of the airways in those suffering from asthma. For most people the effects expected would not be large though some individuals may be clinically affected. The effects would be reversed by use of the 'reliever inhalers' used by those suffering from asthma. Exposure to such concentrations may add to the effects of exposure to other pollutants and allergens and thus asthmatics should be warned that they might need to increase medication.
Alert		
VERY HIGH	> 400	As concentrations rise above 400 ppb then more asthmatic individuals may experience adverse effects and should be encouraged to ensure that they have an adequate supply of their 'reliever inhaler'. At any concentrations likely to be experienced in the UK it is very unlikely that normal individuals will experience any adverse effects.

Where:

- A concentration below the threshold level (less than 100ppb as a 15 minute average for SO_2, for instance) is described as a LOW level of air pollution;
- A concentration measuring between the threshold level and 'information' would be described as MODERATE;
- A concentration measured between 'information' and 'alert' thresholds is described as HIGH;
- A concentration measured above the 'alert' threshold is described as VERY HIGH.

The COMEAP report

The Committee on the Medical Effects or Air Pollutants (COMEAP) was commissioned by the Department of Health to report on the extent of effects of air pollutants on health in the UK and to estimate the numbers of people affected.

COMEAP produced a report entitled 'Quantification of the Effects of Air Pollution on Health in the United Kingdom'. The report considers particulate matter, sulphur dioxide, nitrogen dioxide, ozone and carbon monoxide.

The complete chapter on sulphur dioxide from the COMEAP Report is given in Annex V.

Annex V
COMEAP report extract

This extract from the Department of Health's Committee on the Medical Effect of Air Pollutants (COMEAP) Report entitled 'Quantification of the Effects of Air Pollution on Health in the United Kingdom' provides additional information on the potential health effects of sulphur dioxide air pollution.

The COMEAP report uses µg/m³ for atmospheric concentrations, whereas this report uses ppb. An approximate conversion is 1 ppb = 2.66 µg/m³, e.g. 50 µg/m³ = 18.8 ppb.

Chapter 4 Sulphur Dioxide

Introduction

4.1 Sulphur dioxide (SO_2) is a colourless, soluble gas with a characteristic pungent smell. It is produced by the combustion of fossil fuels that contain sulphur- and has been monitored for many years in ambient air in the UK because of the damage it causes to the environment as well as its health effects. During recent years the use of coal for domestic heating has declined in Britain and other West European countries, with a consequent reduction in atmospheric SO_2 concentrations. Coal-fired power stations are now the major source. Atmospheric SO_2 levels tend to fluctuate widely from day to day, particularly in large cities and also show a seasonal pattern of variation, levels tending to be higher in the winter, although this seasonal pattern is much less marked than was the case before the Clean Air Act of 1956.

4.2 It has long been recognised that SO_2 is a potent respiratory irritant when inhaled acutely in the laboratory at levels achieved during exceptional air pollution conditions. This is especially the case in patients with asthma. Of the pollutants dealt with in this report, SO_2 is the only one for which there is clear clinical evidence of increased sensitivity amongst asthma sufferers. Over the last decade or so, SO_2 had come to be regarded as less important as a pollutant from the health point of view than previously, though recent studies, largely from Europe, have clearly identified this gas as a continuing cause of effects on health.

4.3 This section attempts to quantify the effects of SO_2 on human health. It examines the evidence relating to both acute and chronic effects, drawing on the results of meta-analyses where possible.

Acute effects

4.4 A number of published studies have examined the relationships between concentrations of SO_2 and daily variations in various indices of health, such as number of deaths, hospital admissions and (in panels of patients or healthy volunteers) symptoms or indices of lung function. There are certain difficulties in interpreting these relationships. Like other atmospheric pollutants, SO_2 tends to accumulate in some weather conditions and disperse in others, so many of these studies have attempted to allow for potential confounding factors such as season and temperature. Circumstances that favour a rise in SO_2 are likely to cause a rise in other pollutants, and it is not always easy to be sure which pollutant is responsible for an observed effect on health, or whether an effect is attributable to a pollutant that was not measured. In some areas, particulates and SO_2 arise from the same sources and are therefore especially correlated, so that it is sometimes difficult to distinguish between their effects. Also, SO_2 contributes to air pollution by the secondary formation of sulphate particles. It is also uncertain as to whether acute effects might be greatest on the same day as a peak of SO_2, or on a subsequent day, so different studies have 'lagged' the correlations with health indices by different numbers of days or, not at all.

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Mortality

4.5 A meta-analysis has been performed on the results of the APHEA project which has the advantage that, within the limits of the APHEA project, it is free from the biases that often affect meta-analyses due to incomplete ascertainment or failure to include relevant studies (publication and selection biases); furthermore, the data were easily combined because of the common protocol. There were, however, some differences between the statistical analyses conducted on the various centres' data: for example, each centre determined from its own data the lagging interval that gave the closest correlations between particle concentrations and effects on health. For all-cause mortality, a substantial degree of heterogeneity was found between the data from Western European cities on the one hand and Central and Eastern European cities on the other hand. The Western European data are probably more relevant to the UK, particularly as London was one of these centres, so only these data will be presented here. The distinction between Western and Central plus Eastern Europe was already defined in the protocol as a potential determinant of heterogeneity, so this restriction is not subject to the bias that might arise if it were arrived at post hoc from the data.

4.6 Table 4.1 shows the relative risks associated with a rise of 50 μg/m³ in the daily average SO_2, concentration. For all-cause mortality the estimate is based on seven Western European cities and corresponds to a 3% rise in total deaths. Although this is very unlikely to be a chance effect (the confidence limits show that the true effect is probably between 2.3% and 3.5%), there was a significant degree of residual heterogeneity in the model - i.e. the relationship between SO_2 and mortality may not be the same in all these seven cities. In the Central and Eastern European cities the relationship was much weaker and not statistically significant. For cardiovascular and respiratory mortality the data relate to five cities and show increases (highly significant statistically) of 4% and 5% respectively for each 50 μg/m³ rise in SO_2.

4.7 These findings are broadly consistent with reports from other studies. A recent review by Lebowitz identified seven studies of SO_2 and mortality in which daily SO_2 levels exceeded 80 μg/m³, and six of these showed a significant association. In East Berlin during the winters of 1981-1989, mortality increased by 2.3% for each 50 μg/m³ rise in SO_2, after excluding days when concentrations exceeded 150 μg/m³.

4.8 It is unclear what mechanism could be responsible for these substantial effects. One question that must be considered is whether episodes of pollution merely hasten deaths that would have occurred within a few days anyway or whether lives have been appreciably shortened. This issue will be addressed below.

Table 4.1 Changes consequent upon a rise in SO_2 of 50 μg/m³ (24h average): Summary of APHEA estimates for SO_2 in Western European cities

OUTCOME	AGE	NO CITIES	RR	95% CL
All cause mortality		7	1.029*	1.035,1.023
Cardiovascular mortality		5	1.04	1.06,1.10
Respiratory mortality		5	1.05	1.03,1.07
Respiratory admissions	1 5-64 yr	5	1.009	0.992,1.025
	65+yr	5	1.020	1.005,1.046

* Fixed effect model

Hospital admissions

4.9 Table 4.1 also shows the effects of SO_2 on admissions to hospital for respiratory diseases from the APHEA data. Under the age of 65 years there is no significant effect but above this age an increase of 50 µg/m³ is associated with 2% more admissions. Other studies have shown associations of varying strengths. In Barcelona (another APHEA centre) an increase of 25 µg/m³ was associated with increased emergency room attendances amounting to 6% in winter and 9% in summer, after adjusting for other variables. Positive associations with respiratory admissions in the elderly have also been reported in two American cities, and with asthma admissions in Birmingham UK and in Oulu, Finland. In Birmingham, the effect appeared to vary with the season, the greatest being seen in winter.

Other acute effects

4.10 A number of workers have followed up groups of persons, usually with known respiratory disease, to see whether fluctuations in pollution levels are reflected in variations in daily symptoms or lung function indices. For example, in a panel of 73 Dutch children with chronic respiratory symptoms, SO_2 was associated positively with wheeze and bronchodilator use and negatively with peak expiratory flow rates. This was attributable to an episode in which 24-hour, average SO_2 concentrations rose to 105 µg/m³ and PM exceeded 105 µg/m³. A British study of 75 adults with chronic respiratory disease showed similar associations, although the SO_2 levels did not breach WHO guidelines during the course of the study. Other examples are listed by Lebowitz. These findings confirm the impression that fairly small changes in SO_2 levels call have a range of effects upon health which are not confined to bringing forward the deaths of seriously ill individuals, although it is difficult to separate the effects of SO_2 and particulates in some of these studies.

Chronic effects

4.11 A number of studies have examined the effects on health of long-term exposure to differing average concentrations of SO_2. There are a number problems associated with such studies of chronic effects of air pollutants: these have been discussed in Chapter 2, paragraph 2.28 [of the COMEAP Report].

Mortality

4.12 Geographical studies relating death rates to exposure levels have suggested that an association exists which does not seem to be entirely explained by the obvious confounding variables. A study in different regions of the Czech Republic found a strong association between SO_2 exposure and the respiratory mortality of infants aged one month to one year; number of deaths between areas with the highest and lowest quintiles of exposure (annual geometric means > 57.9 and < 12.5 µg/m³, respectively) differed by a factor of 5.41 after adjusting for socio-economic variables, and by 3.91 when particulate and NO_x levels were allowed for. There was also a relationship with particulate exposure, and it may prove to be impossible to separate the effects of these pollutants, since they tend to be associated with each other. Quantifying the effect is also very difficult; the Department of Health's Advisory Group on the Medical Aspects of Air Pollution Episodes was not able to address the question of exposure-response on the basis of existing data, although there was evidence of a qualitative relationship.

4.13 A Japanese study of two areas partly circumvented the problem of confounding because one area showed first a worsening and then an improvement in air pollution over a period of 21 years. As air pollution deteriorated, mortality due to asthma and chronic bronchitis increased; when air quality improved, asthma mortality decreased immediately and chronic

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bronchitis mortality declined gradually, reaching the level in the unpolluted area 4-5 years after SO_2 concentrations began to satisfy air quality standards.

Symptoms and lung function

4.14 In relation to symptoms, the Department of Health Advisory Group arrived at a 'qualified judgement about exposure-response' on the basis of selected studies as follows. An annual mean concentration of 24-hour mean SO_2 of 60-140 µg/m³ is associated with increased respiratory symptoms in adults. At 140-200 µg/m³ associations have been reported with increased respiratory illnesses in children. There are no clear indications of a threshold level. Some of the relevant studies did not control for environmental tobacco smoke.

4.15 Lebowitz notes the association between SO_2 and the prevalence of chronic obstructive pulmonary disease (COPD); he estimates a relative risk for COPD of 1.5-2.5 as the annual SO_2 and TSP concentrations concurrently exceed 100 µg/m³.

4.16 A study in Arizona compared the respiratory health of children in four areas that had different degrees of air pollution. The children were followed up so that the incidence of symptoms and the changes in lung function could be recorded. The degree of SO_2 pollution was correlated with the prevalence but not the incidence of symptoms, while the development of lung function with age was roughly the same in the four areas. It was concluded that intermittent elevations in SO_2 concentrations, in the presence of moderate particulate sulphate levels, cause some bronchial irritation but no chronic effects.

4.17 Lebowitz summarises the evidence on lung function by stating that significant decrements of 3-8% in FEV appear to be related to ambient annual SO_2 and sulphate concentrations above 100 µg/m³ in children. Decreases occur more frequently and are greater in those starting with low lung function, bronchial hyper-responsiveness and chronic respiratory disease.

Conclusions

4.18 There is little doubt that SO_2 both causes and aggravates symptoms particularly in patients with pre-existing asthma. In association with particles, it appears to increase mortality both in the short- and the longer-term, although it is uncertain which component of pollution is mostly responsible. The associations with raised mortality do not seem to be attributable simply to a more rapid demise of people who are dying in any case, since there is some evidence that death rates in chronically polluted areas remain substantially higher than those of cleaner areas. The best current estimates of the acute effects are that each 50 µg/m³ rise in the 24-hour average concentration raises the death rate by 3% for all causes, 4% for cardiovascular diseases, and 5% for respiratory diseases. It is much more difficult to quantify the chronic effects at present and we take the view that exposure-response relationships for chronic effects for the UK are not devisable.

Annex VI
Meteorological figures

This annex contains a number of detailed meteorological figures for the period of the episode:

- Tephigram for Nottingham Watnall for 2-9-1998 at 11:15 GMT;
- Tephigram for Nottingham Watnall for 2-9-1998 at 17:15 GMT;
- Mean sea level pressure for 2-9-1998 at 00:00 GMT;
- Mean sea level pressure for 3-9-1998 at 00:00 GMT.

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About Nottingham Watnall meteorological station

Location	53. N
	1.25 E
Height	117m above sea level

Figure A6.1 Tephigram for Nottingham Watnall 11:15 September 2nd 1998
Ascent time 11:15 UTC 2/9/1998
Surface pressure 1001mb (note hPa = mb)

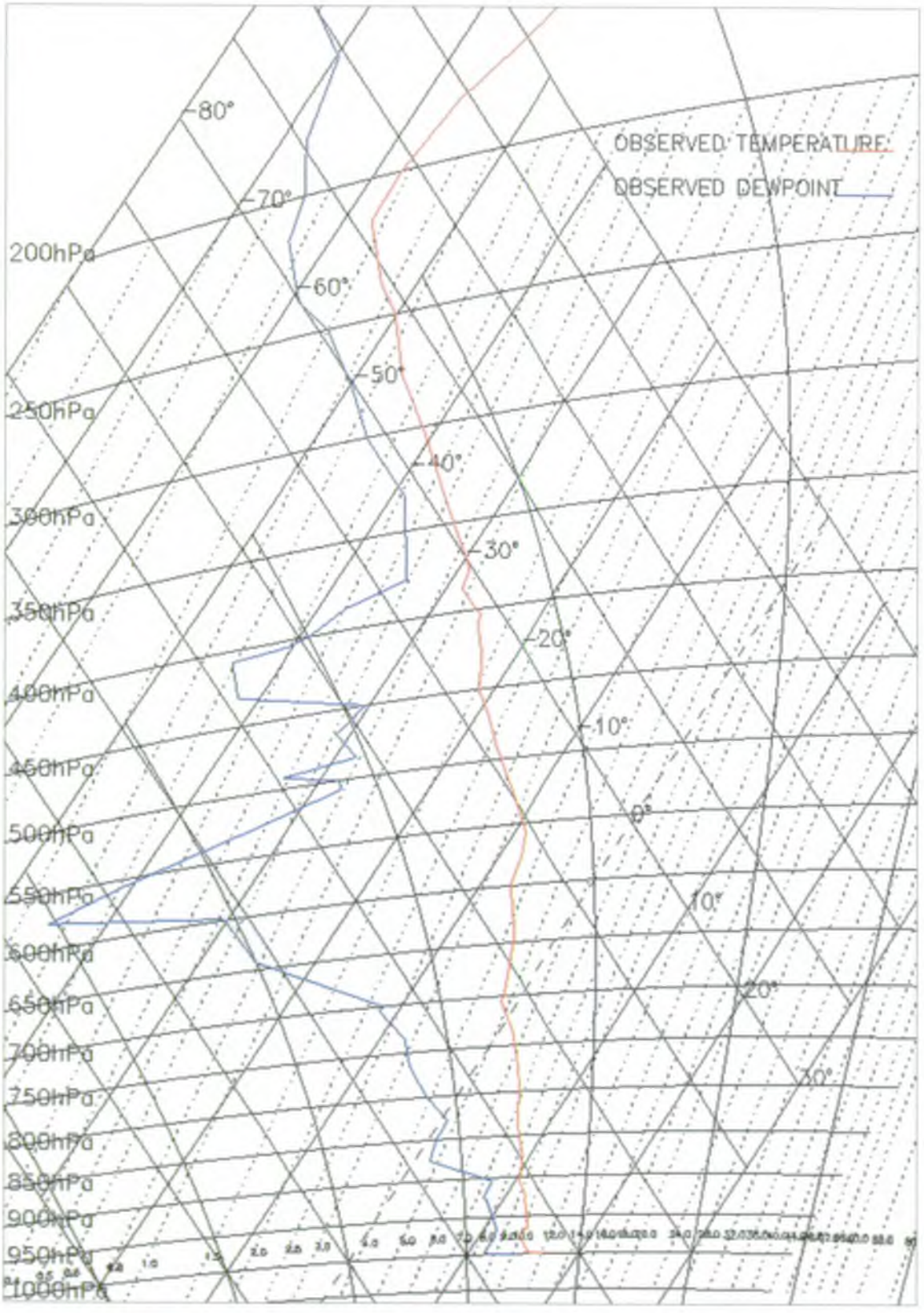


Figure A6.2 Tephigram for Nottingham Watnall 17:15 September 2nd 1998

Ascent time 17:15 UTC 2/9/1998

Surface pressure 1000mb (note hPa = mb)

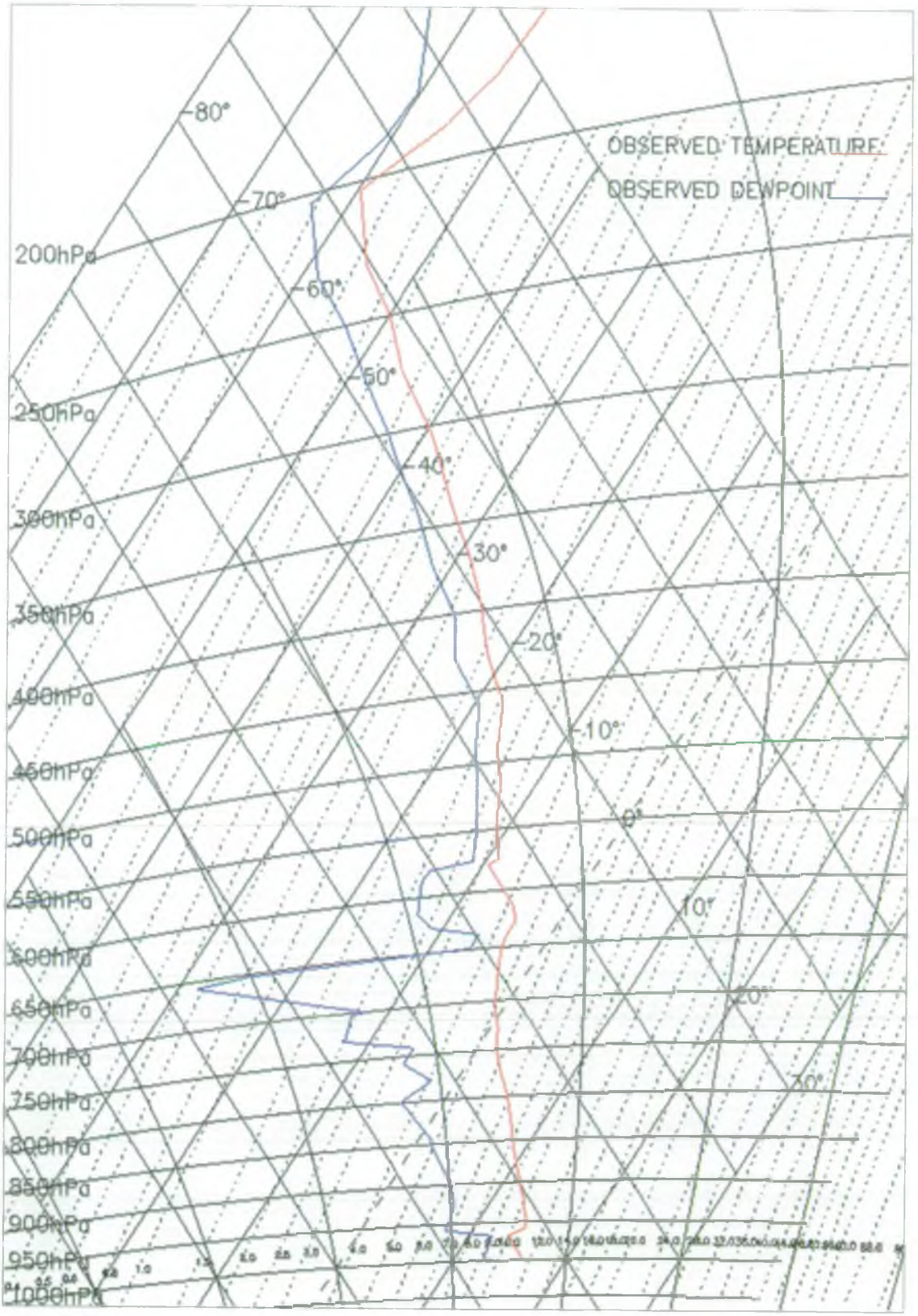


Figure A6.3 Sea level pressure 00:00 September 2nd 1998

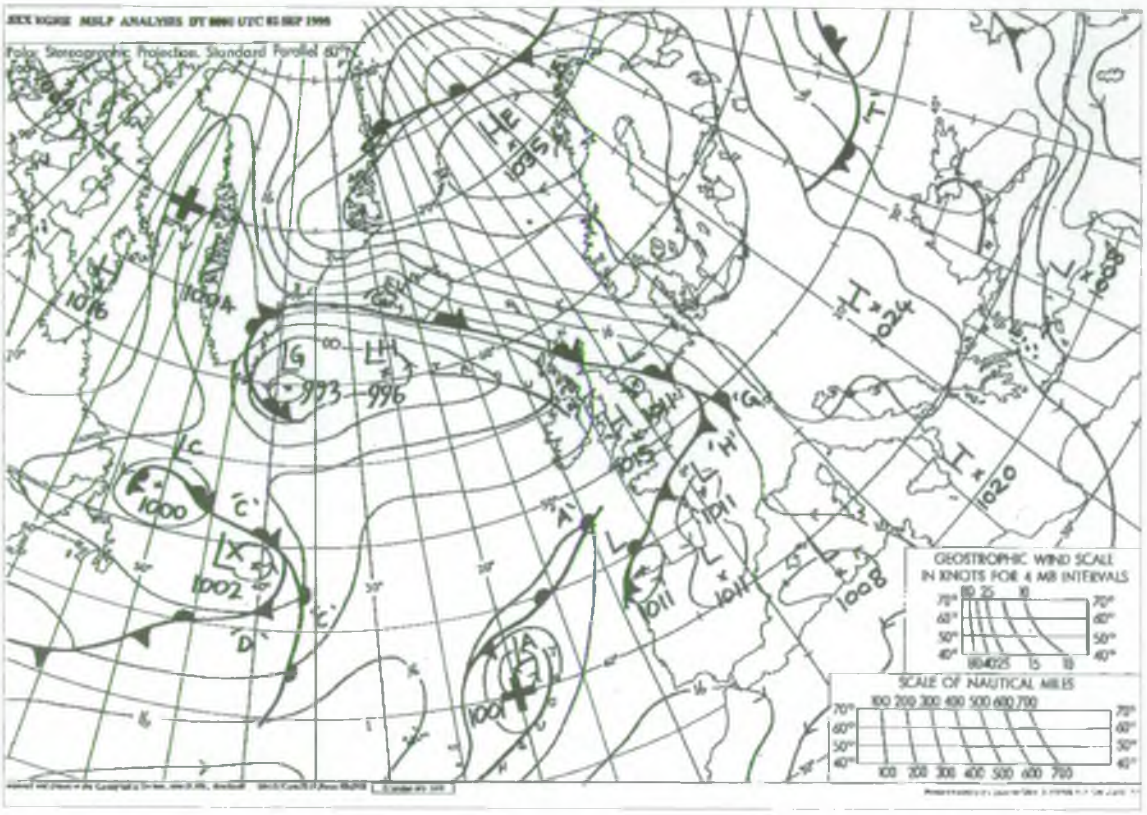
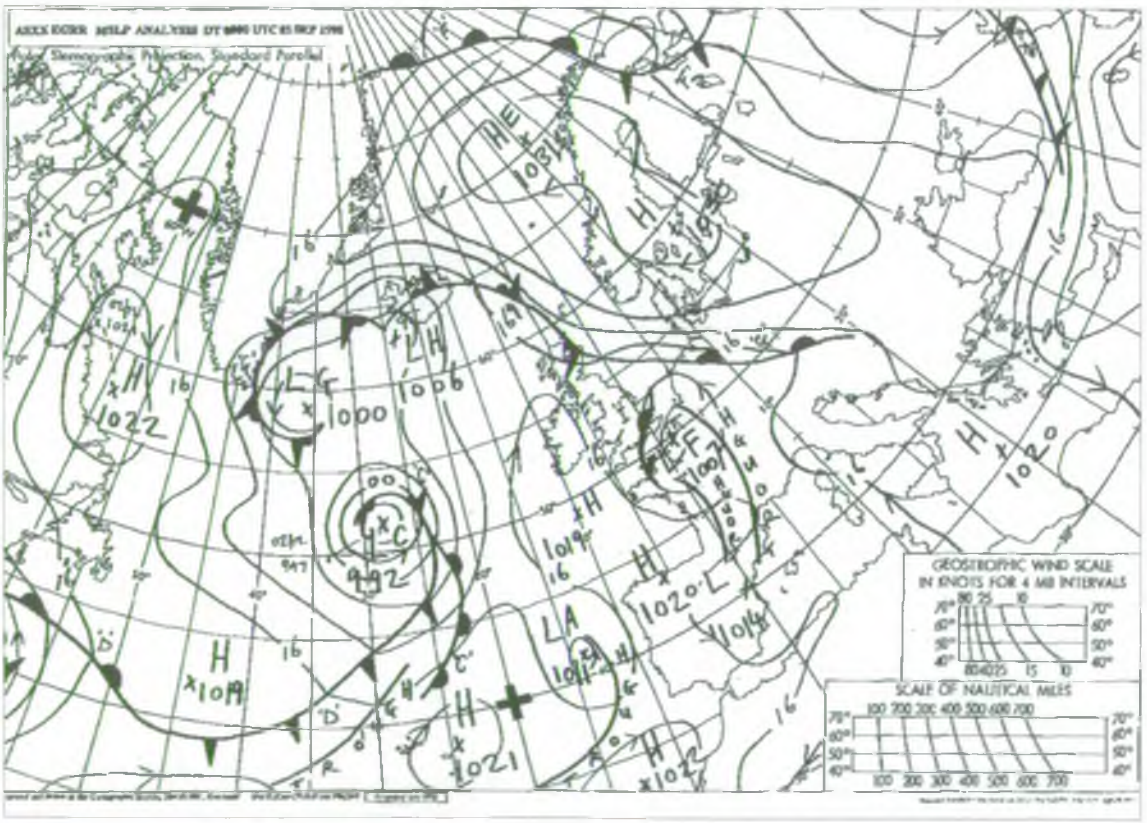


Figure A6.4 Sea level pressure 00:00 September 3rd 1998



Annex VII
NAME results

This Annex contains a variety of graphical outputs from NAME including comparison of monitoring data with NAME output for monitoring stations in the study area (which were operating during the episode), plots of concentration and particle plumes across the study area and a simple analysis of NAME model performance. All of these results report findings without modelling plume rise.

Comparison with monitoring stations

Monitoring results are shown with a red line and predictions with a blue:

Monitoring results — NAME predictions

These charts should be read in conjunction with the concentration plots also contained in this Annex.

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Figure A7.1 DETR Barnsley 12

The chart shows the measured peak for Barnsley 12 arriving about 1 hour later than predicted and does not capture the 'twin peak' character of the monitoring station results. There is also a smaller, late evening peak predicted, however, this 'fit' is acceptable as it captures the main episode within a factor of 2.

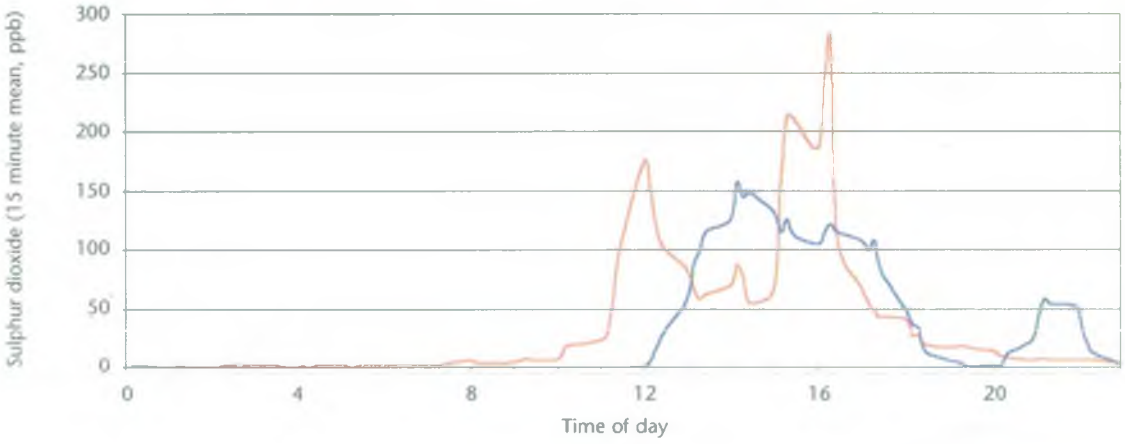

Figure A7.2 DETR Barnsley Gawber

The chart for Barnsley Gawber shows similar characteristics to Barnsley 12.

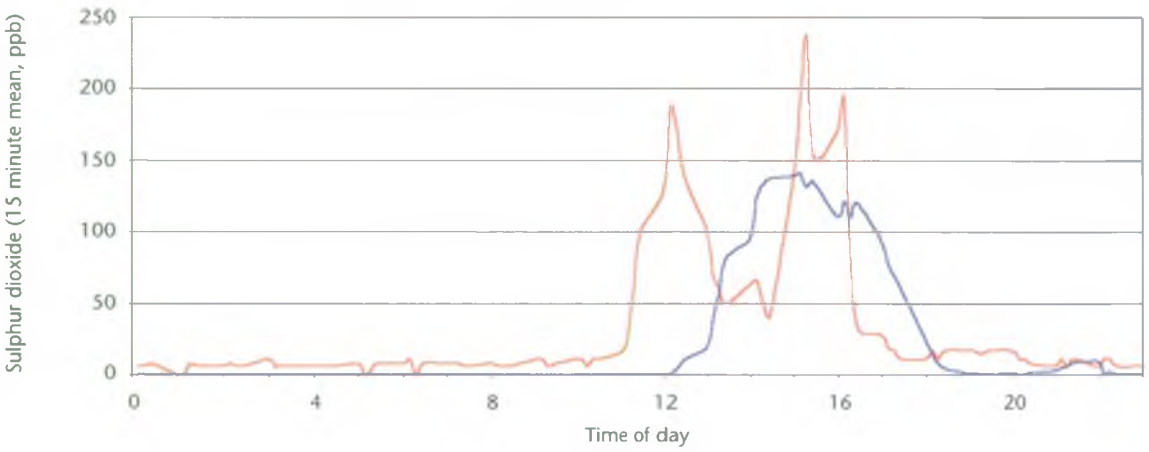

Figure A7.3 DETR Birmingham Centre

The modelled peak at Birmingham Centre shows a good 'fit' in terms of both concentration and time.

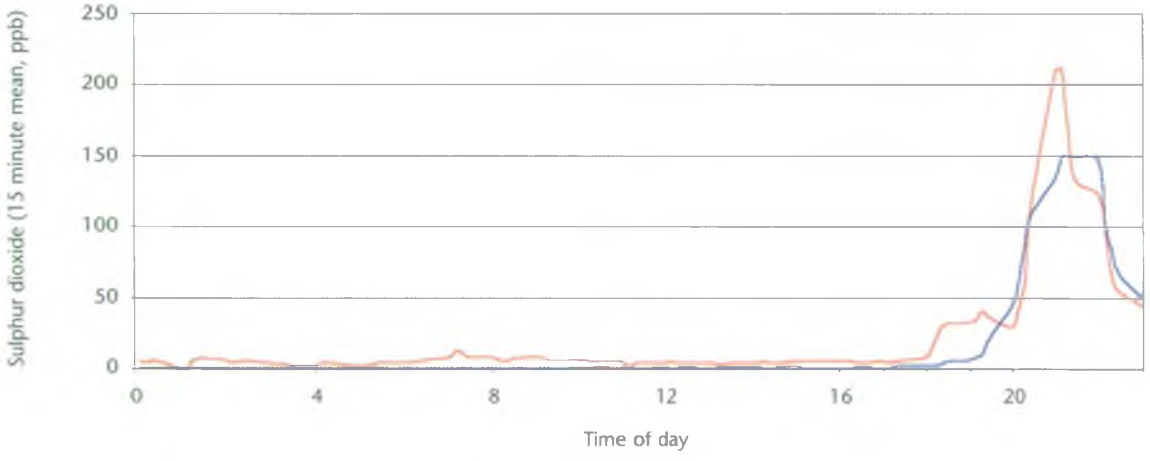

Figure A7.4 DETR Birmingham East

Peak at Birmingham East is modelled exceptionally well in terms of both concentration and time.

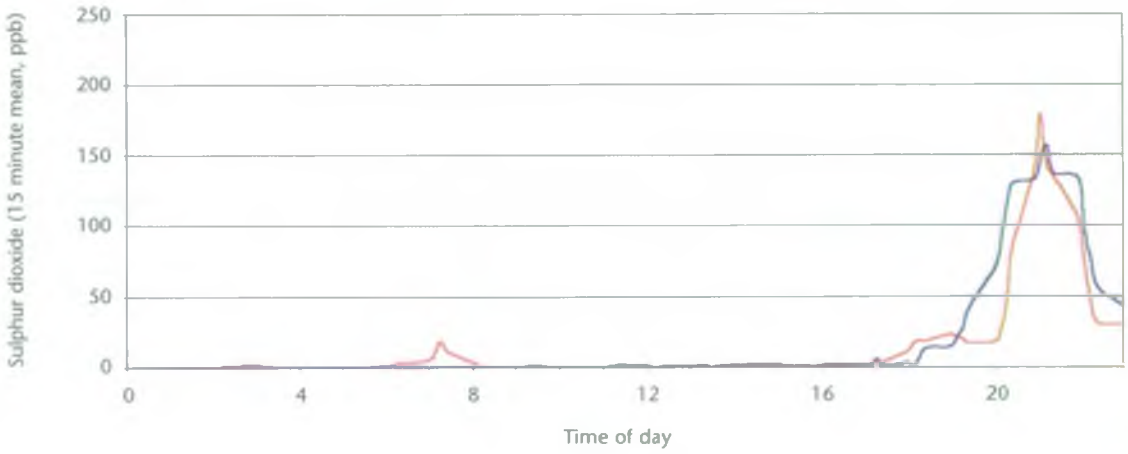

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Figure A7.5 DETR Ladybower

The main peak is captured but the earlier peak is missing. The sulphur dioxide detected as an earlier peak may have been emitted from a process outside the study area, or on the previous day.

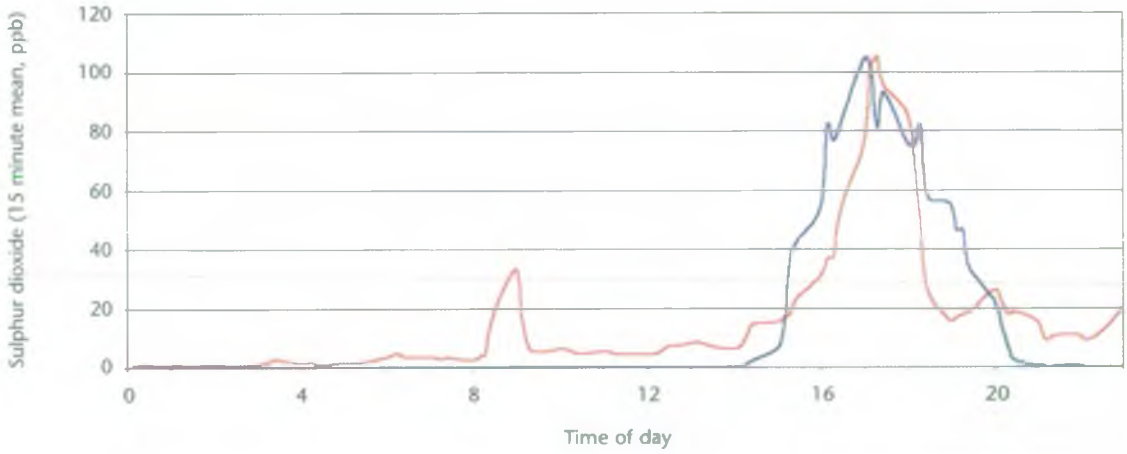


Figure A7.6 DETR Leicester Centre

Leicester Centre lies on the eastern edge of the plume where predictions of concentrations or timing of impacts are sensitive to small changes in meteorology and other input data which have not been accommodated within the NAME modelling, therefore this result is not surprising.

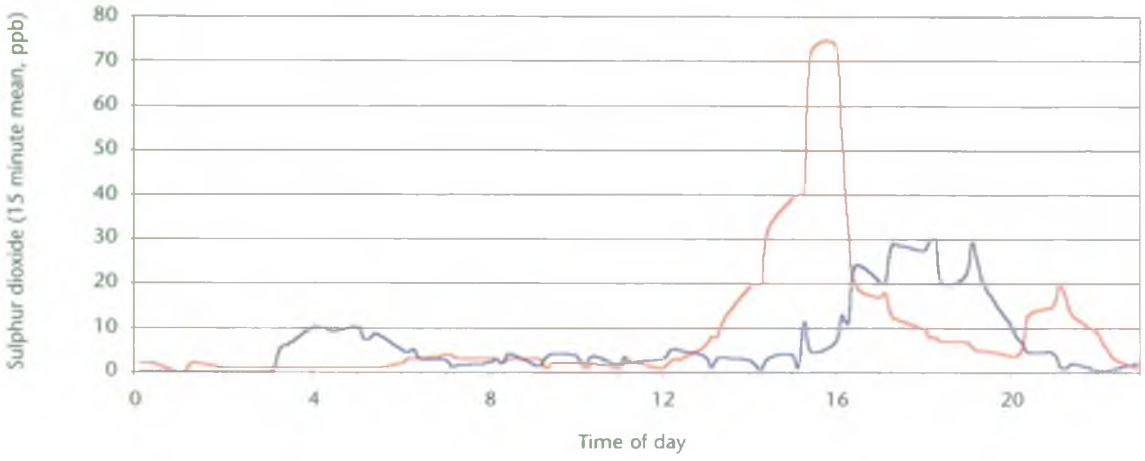


Figure A7.7 Mansfield DC

Mansfield recorded little in terms of sulphur dioxide during the day; examination of the concentration plots shows that impacts predicted in the early hours are from nearby Bolsover. It has been suggested by the Met. Office that this may be due to NAME over-predicting plume spreading. The peak later in the afternoon occurs within the general flow of pollutants and cannot be easily explained.

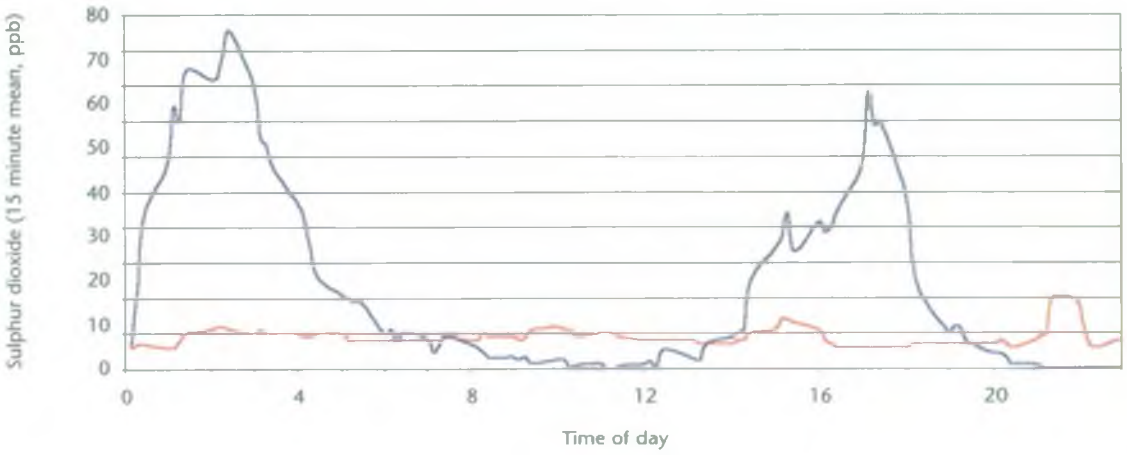


Figure A7.8 DETR Nottingham Centre

The Nottingham peak is the highest recorded during the episode and in many aspects is the most significant. NAME captures the overall timing and concentration with the exception of the highest peak at about 17:00 to 18:00 GMT.

The peak at 23:00 is shown as a plume on the concentration plots. Considering the width of the plume on the map, only a small angular change would be needed to relocate the predicted plume away from Nottingham Centre. This may be due to the meteorology used in NAME.

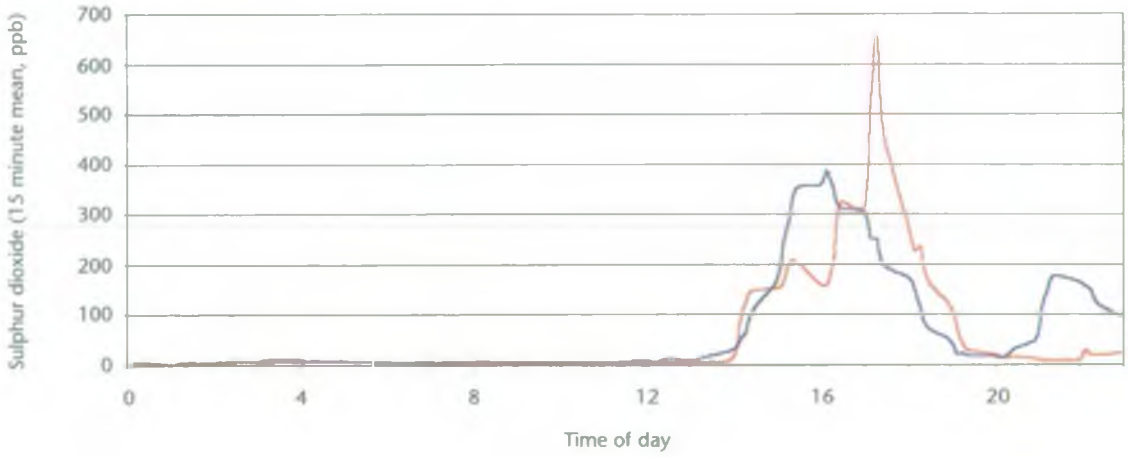
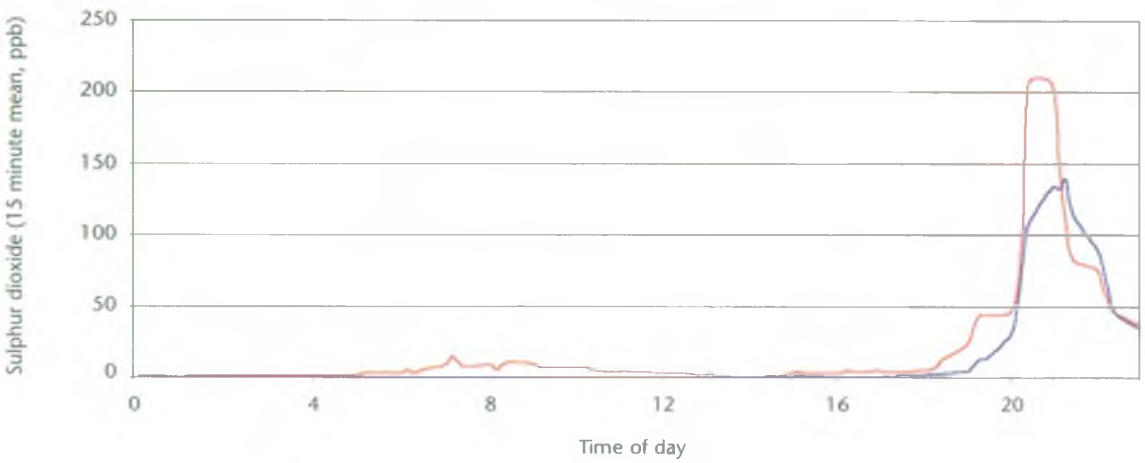


Figure A7.9 DETR Sandwell

Peak at Sandwell is modelled exceptionally well in terms of both concentration and time.



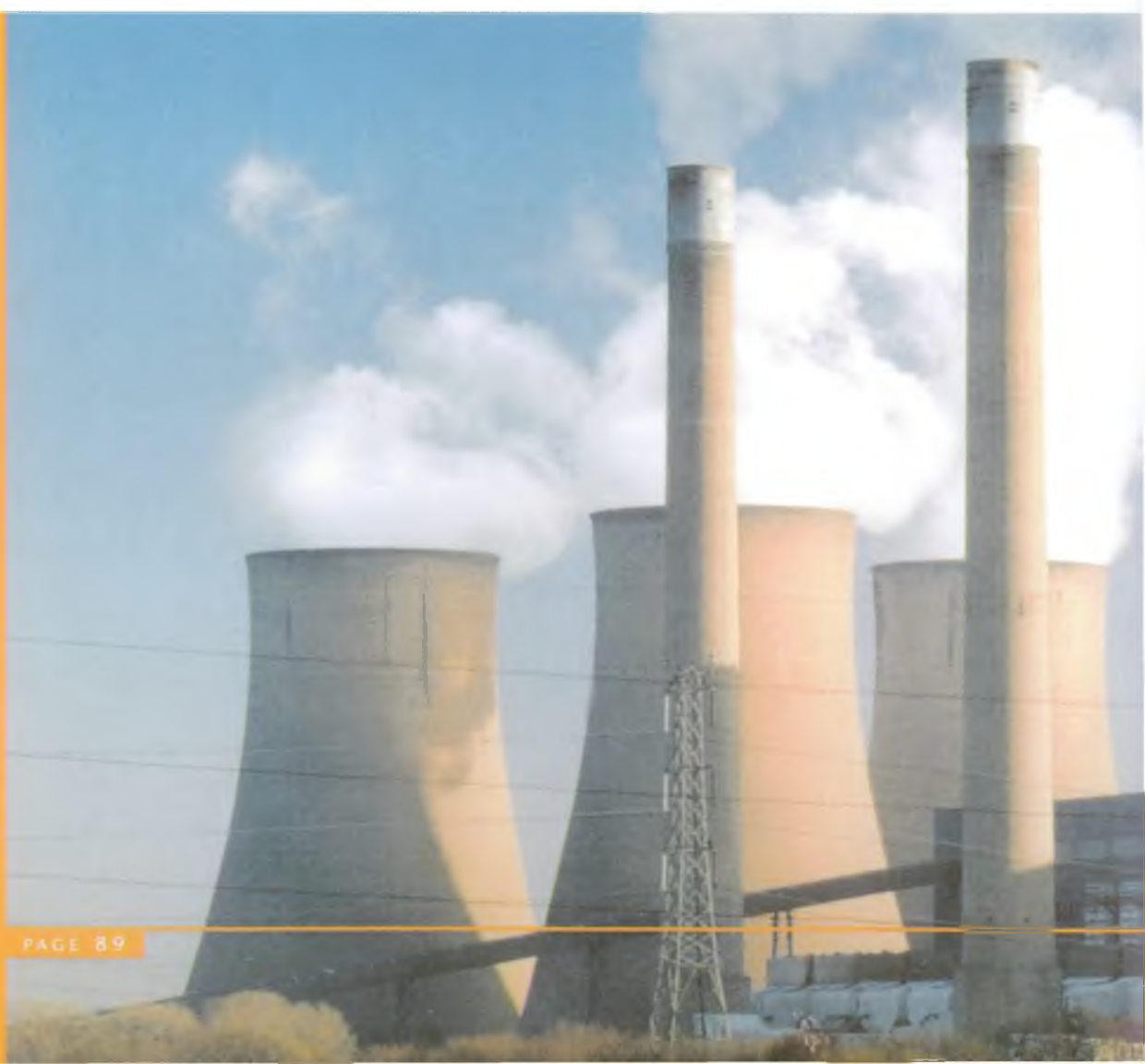


Figure A7.10 DETR Scunthorpe

The early peaks originate from British Steel at Scunthorpe. The monitoring station here is very close to the release source and this is an example of how modelling without including the effects of plume rise, can give a false picture. If Scunthorpe data is run with plume rise then the predicted peaks entirely disappear. For consistency however, predictions modelled without the effects of plume rise have been used throughout this report.

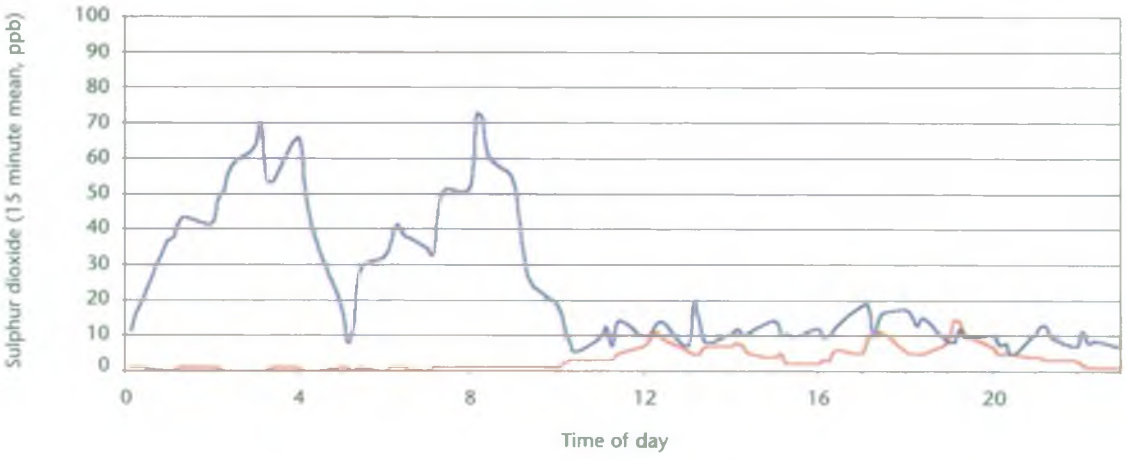


Figure A7.11 DETR Sheffield

Sheffield data is predicted reasonably well in terms of concentration and timing. It is interesting to note the 'twin peak' appearance of the predictions, not apparent in the Barnsley predictions.

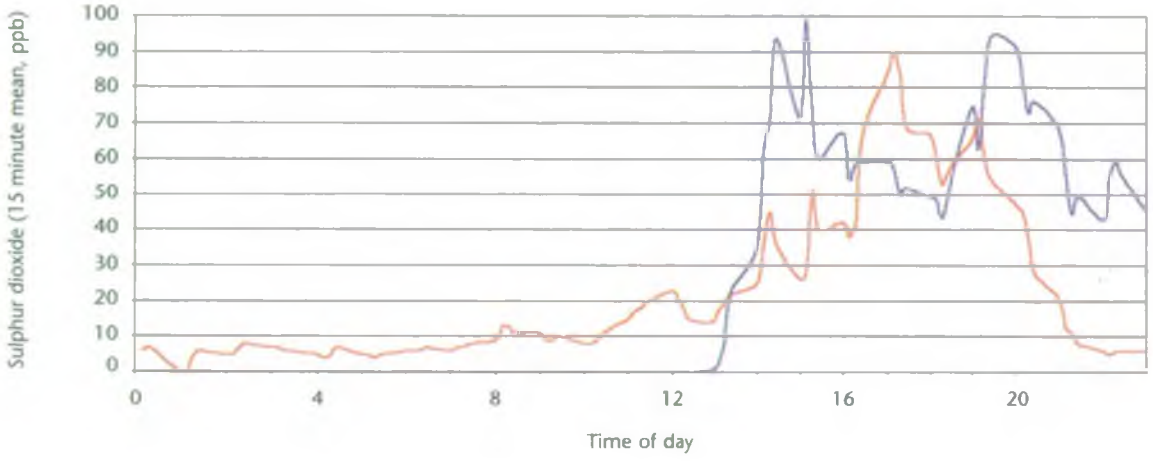


Figure A7.12 DETR Stoke-on-Trent

Stoke-on-Trent lies at the western edge of the study area. Impacts of a similar magnitude is predicted although the timing is relatively poor.

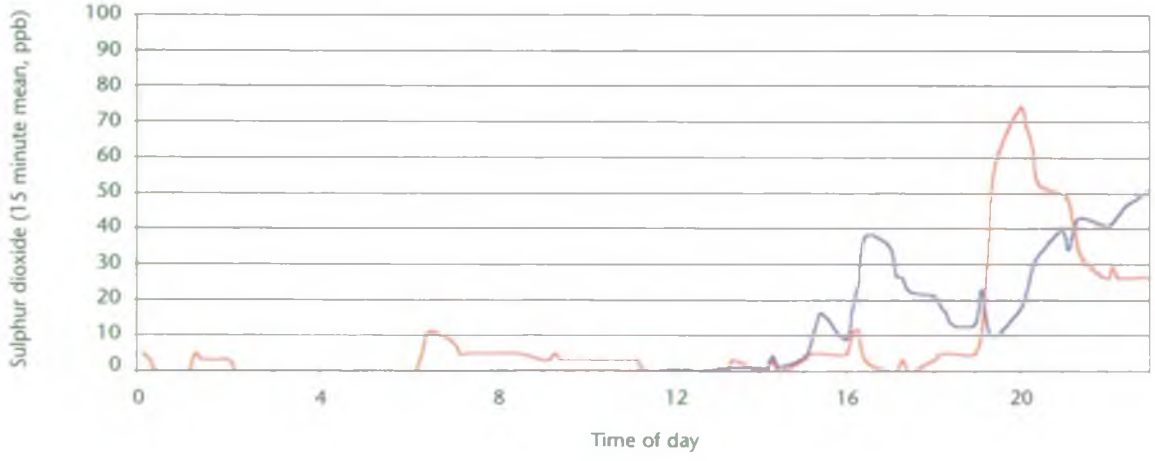
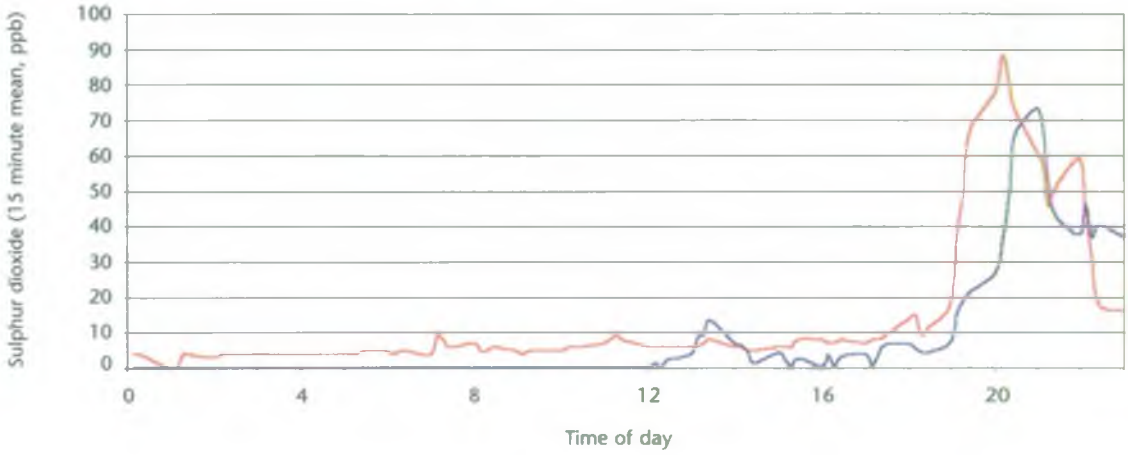


Figure A7.13 DETR Wolverhampton

The Wolverhampton prediction is of a similar magnitude to the actual measured peak but an hour late.



Concentration and particle age plots

This part contains a series of plots covering the study area. There are two types of plot arranged side by side

- The left-hand plot shows the concentration of sulphur dioxide as a 1 hour mean value in ppb. Also shown on this are the sulphur dioxide monitoring stations. The colour of the plot represents the concentration according to the following key:
- The right-hand plot shows the distribution of the particles shown on this plot are the sources of sulphur dioxide used in the NAME study. The colour of each particle (a dot) on this plot represent the time, or age, since the particle was released according to this key:

Concentration key

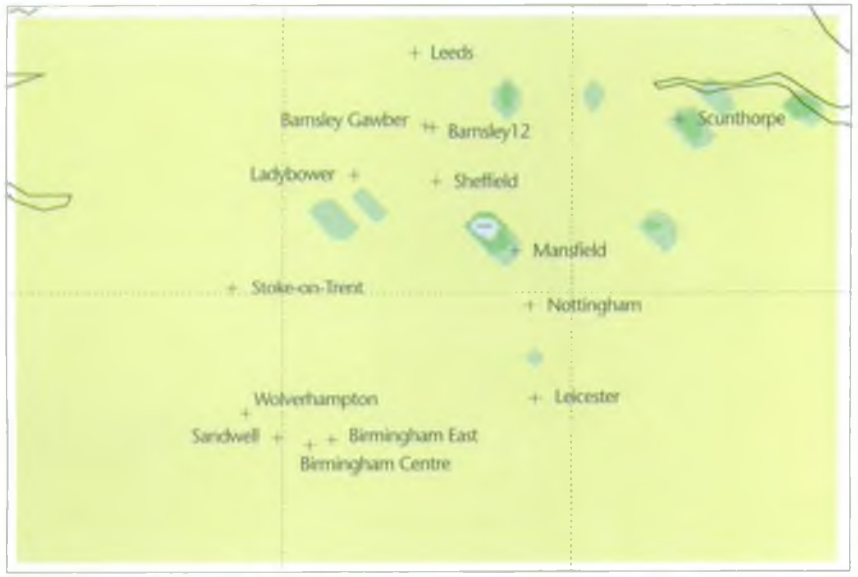
Below air quality standard	Above air quality standard
< 1 ppb	100 – 200 ppb
1 – 10 ppb	200 – 300 ppb
10 – 100 ppb	300 – 400 ppb
	> 400 ppb

Particle age key

0-2 hours	12-14 hours
2-4 hours	14-16 hours
4-6 hours	16-18 hours
6-8 hours	18-20 hours
8-10 hours	20-22 hours
10-12 hours	22-24 hours

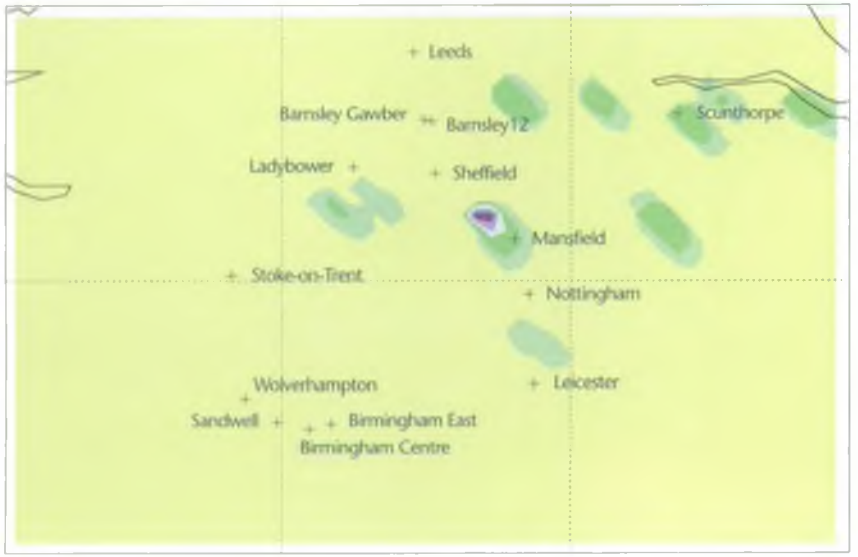
00:00 GMT September 2nd 1998

1 hour mean concentration



Instantaneous plume: boundary layer particles

01:00 GMT September 2nd 1998



02:00 GMT September 2nd 1998

1 hour mean concentration

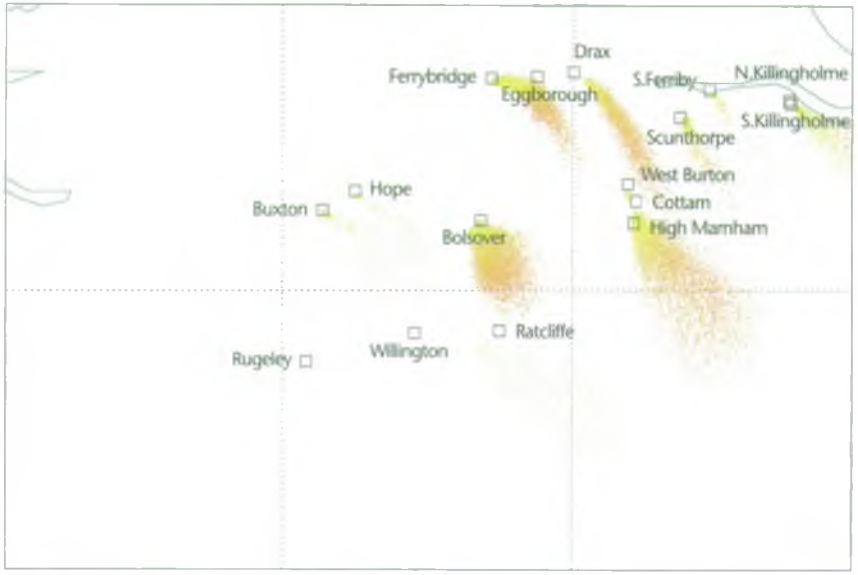
Instantaneous plume: boundary layer particles

03:00 GMT September 2nd 1998

04:00 GMT September 2nd 1998

1 hour mean concentration

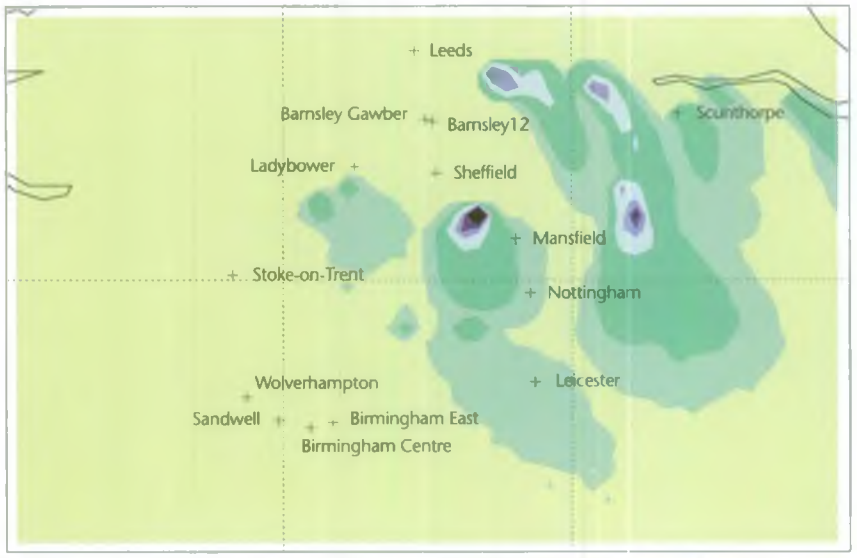
Instantaneous plume: boundary layer particles



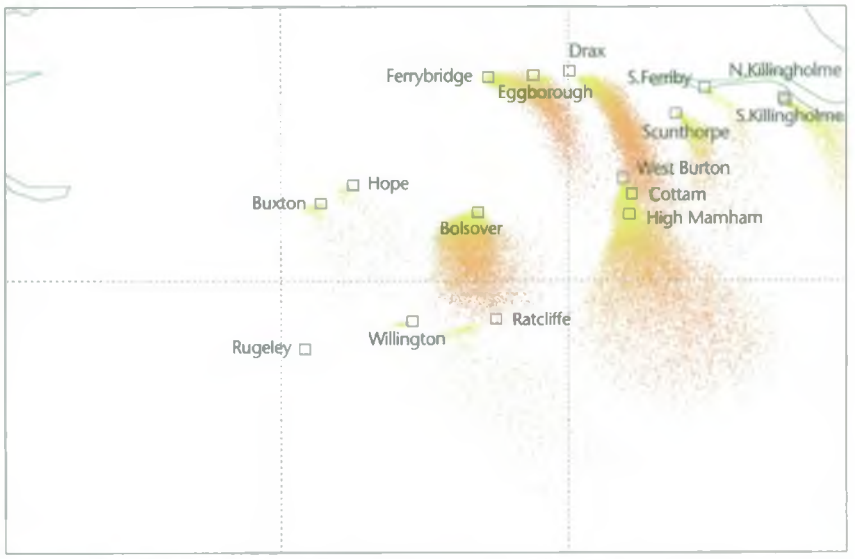
05:00 GMT September 2nd 1998

06:00 GMT September 2nd 1998

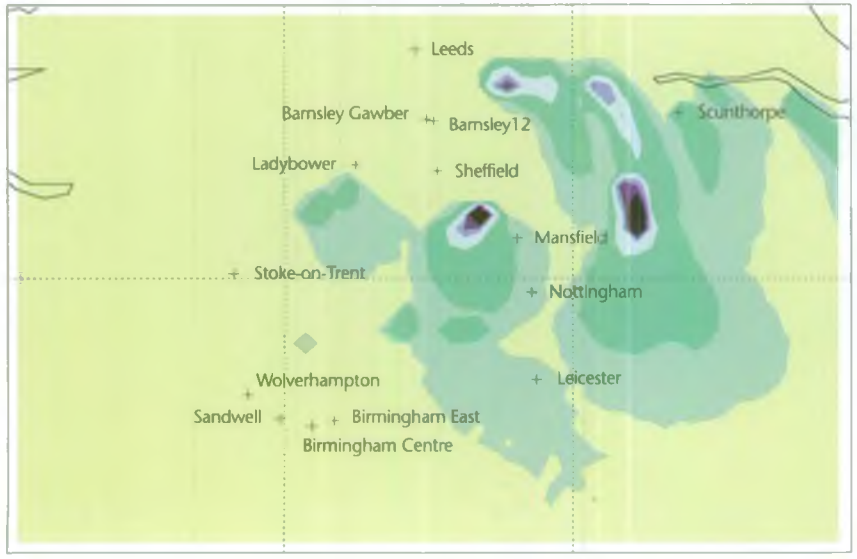
1 hour mean concentration

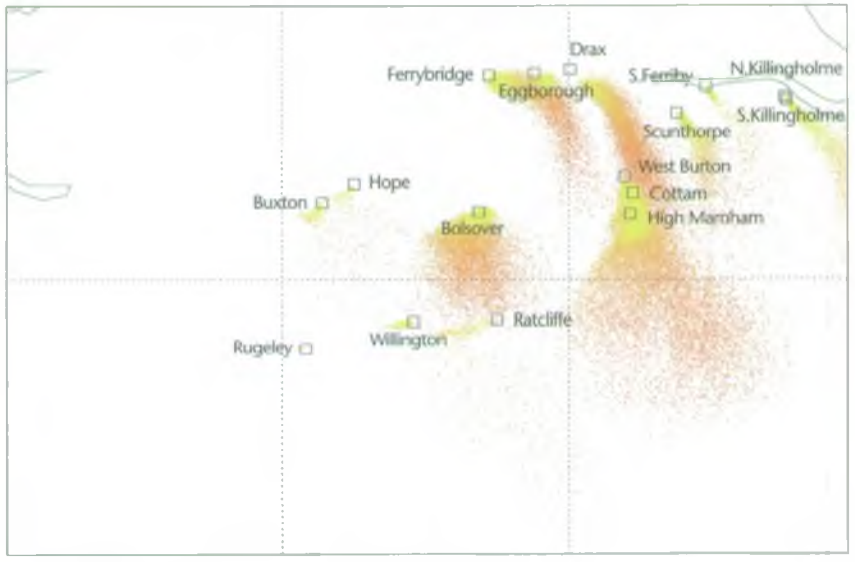


Instantaneous plume: boundary layer particles



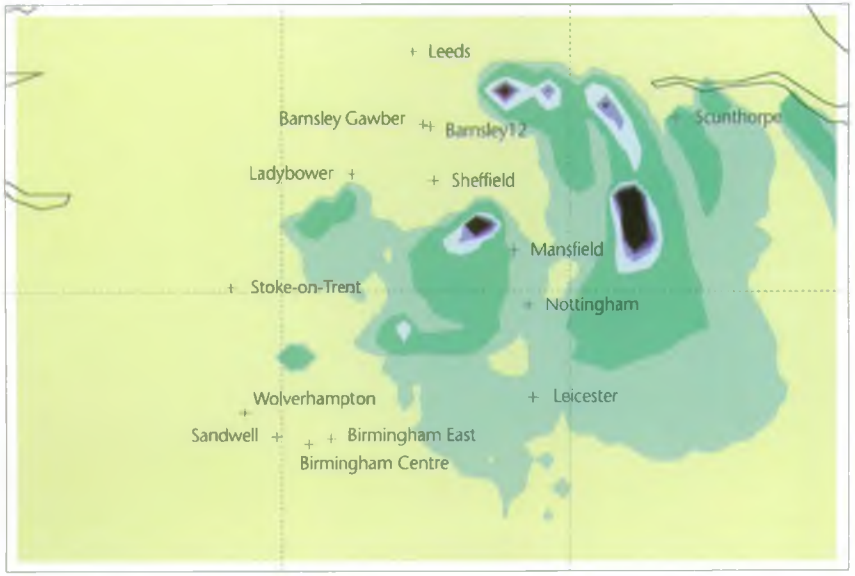
07:00 GMT September 2nd 1998



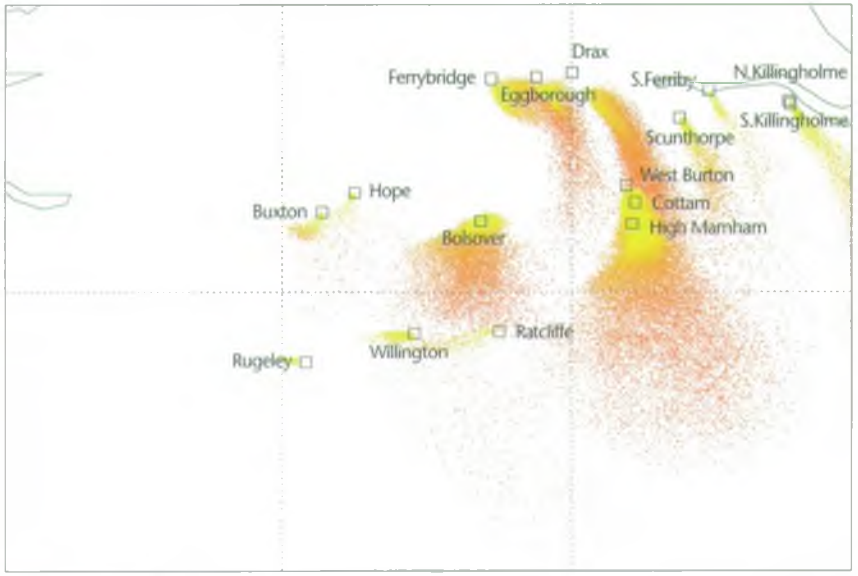


08:00 GMT September 2nd 1998

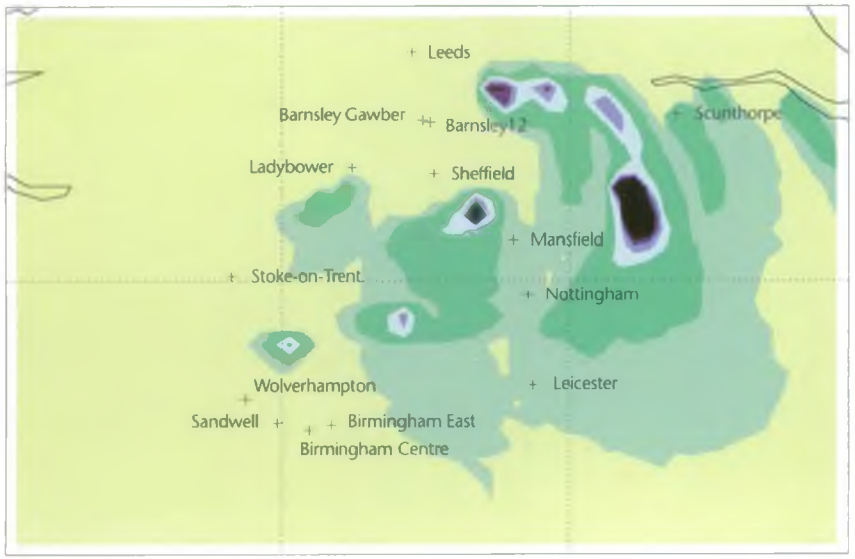
1 hour mean concentration

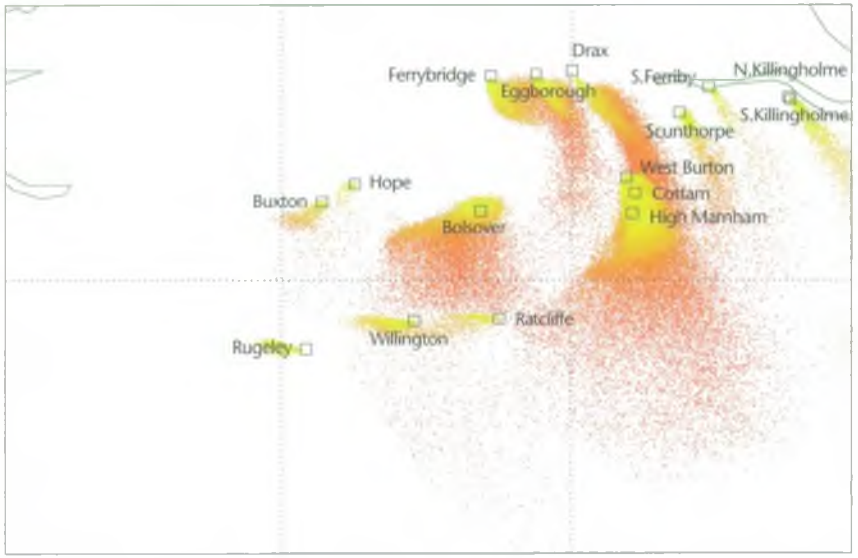


Instantaneous plume: boundary layer particles



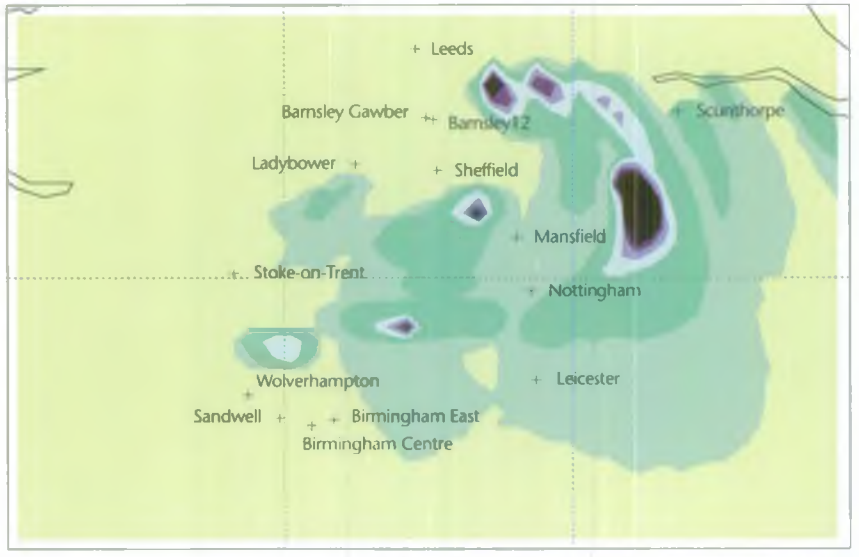
09:00 GMT September 2nd 1998



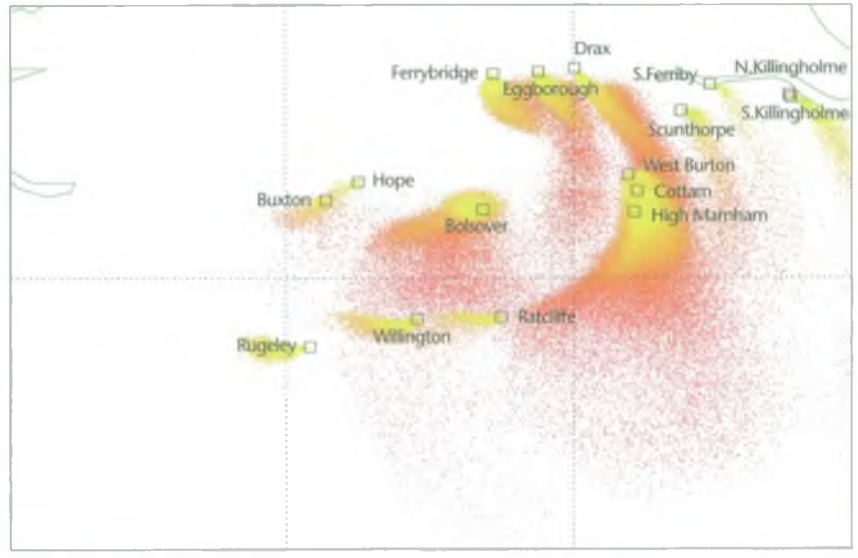


10:00 GMT September 2nd 1998

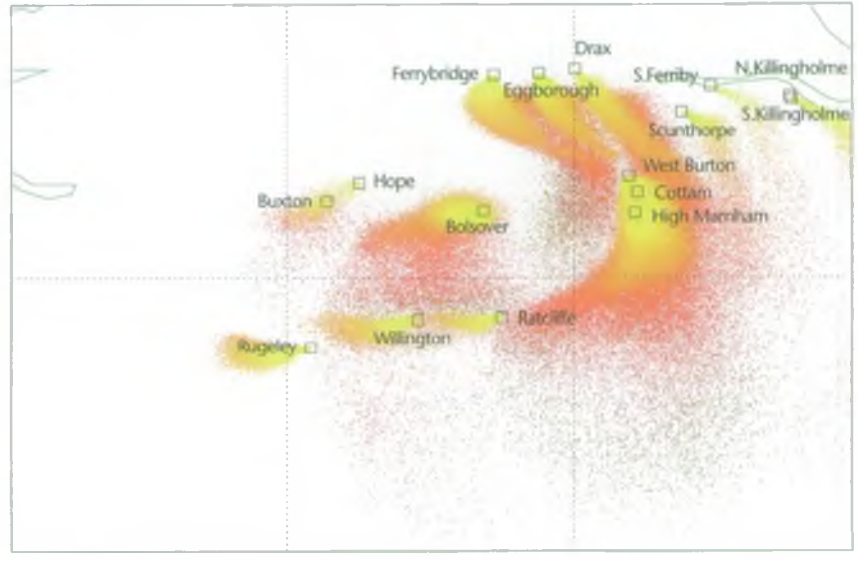
1 hour mean concentration



Instantaneous plume: boundary layer particles

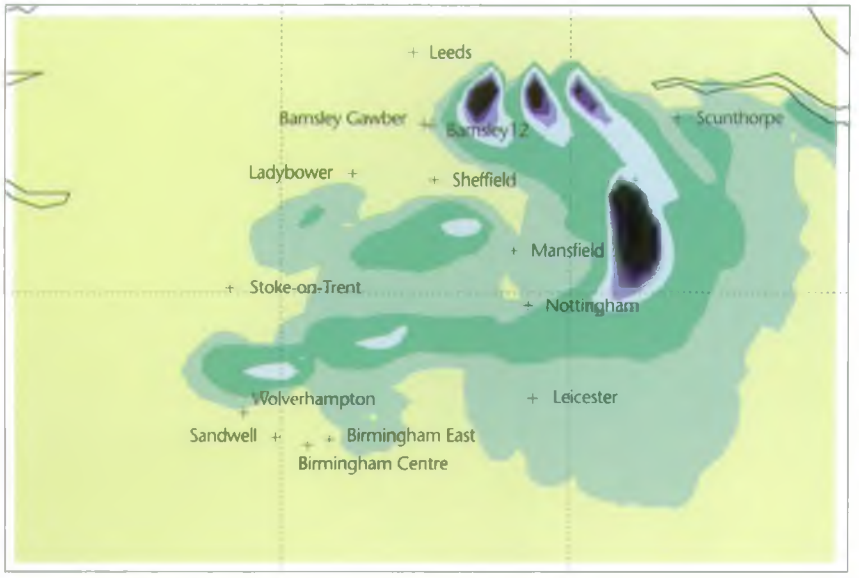


11:00 GMT September 2nd 1998

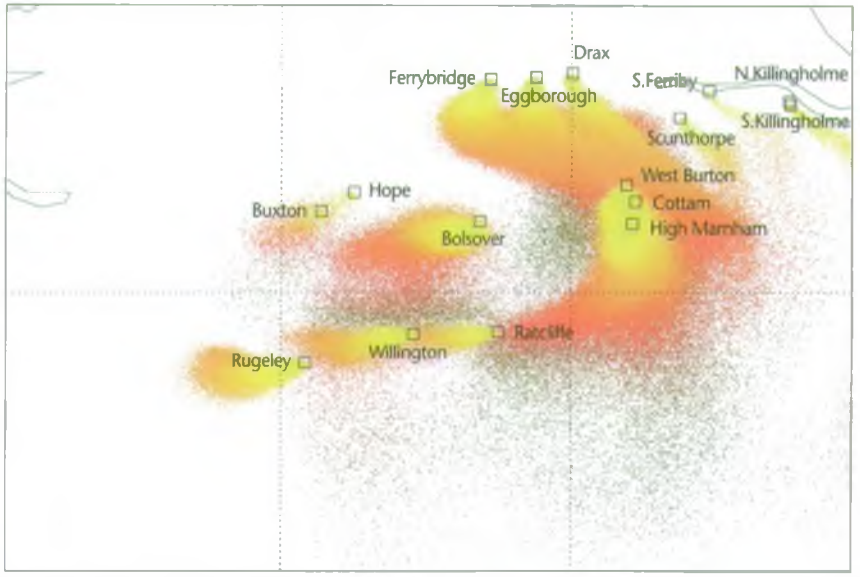


12:00 GMT September 2nd 1998

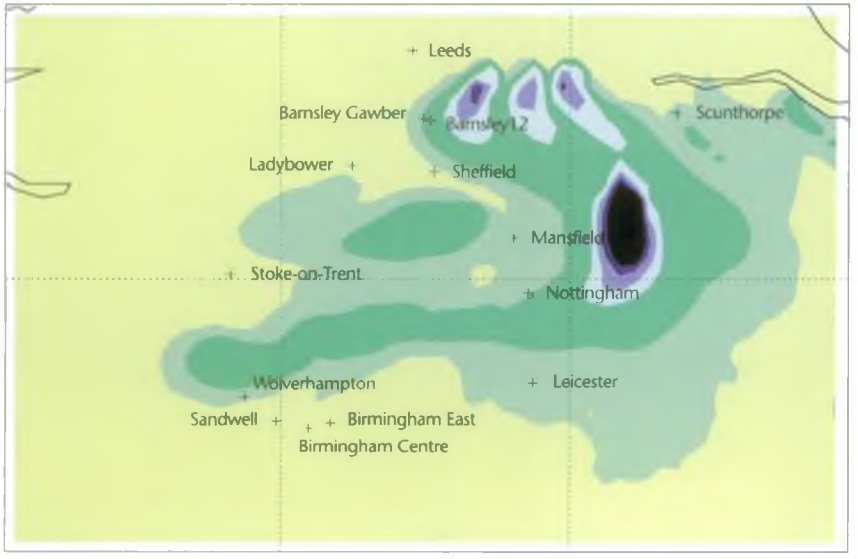
1 hour mean concentration

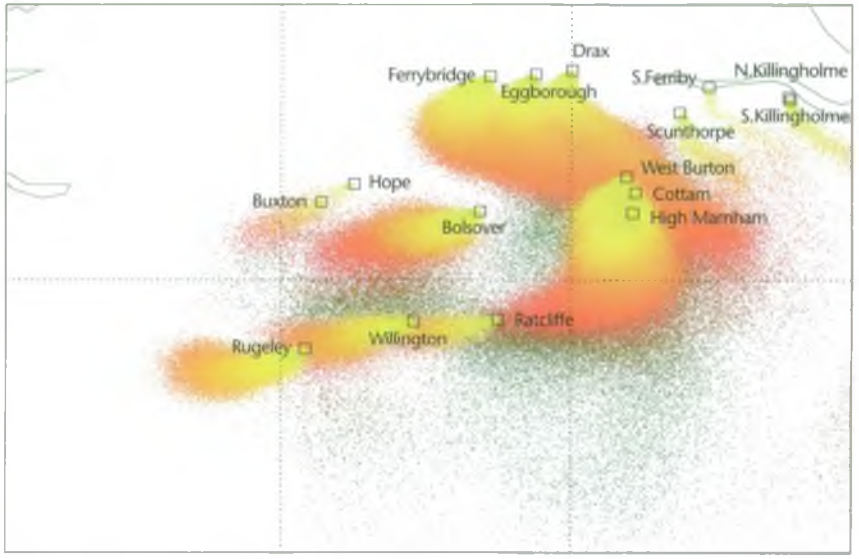


Instantaneous plume: boundary layer particles



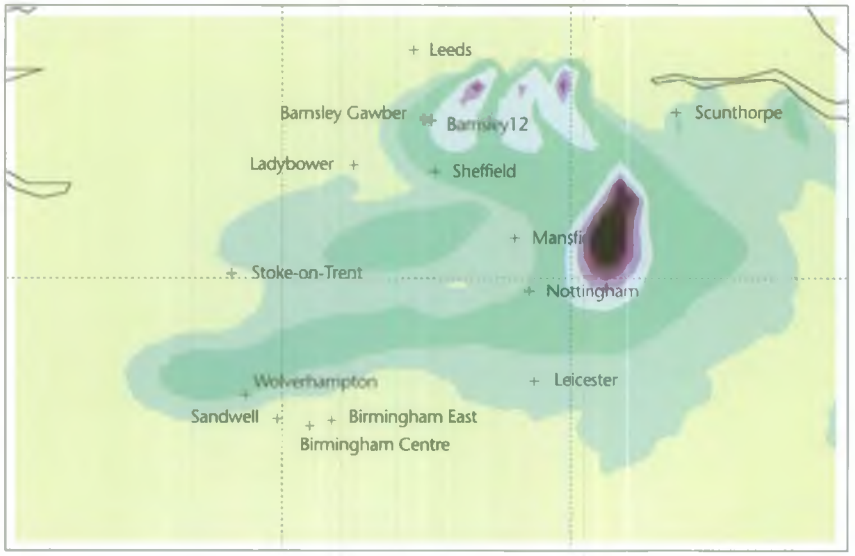
13:00 GMT September 2nd 1998



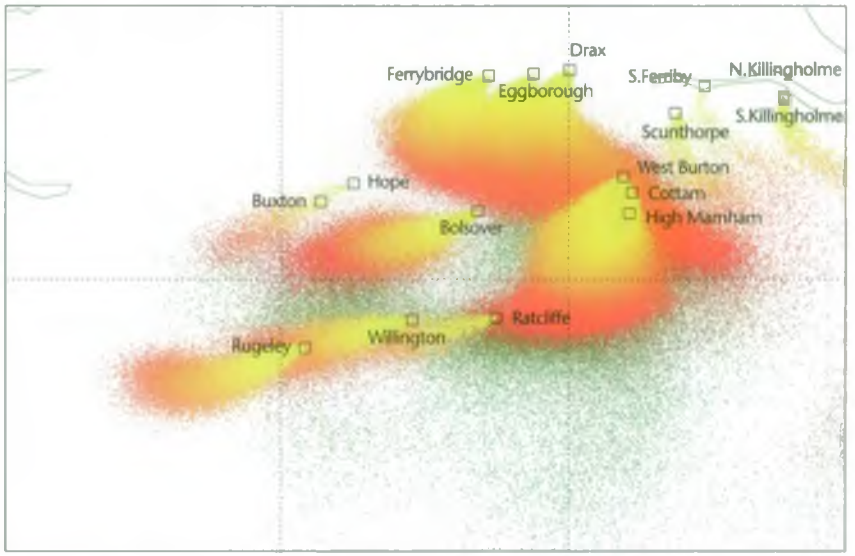


14:00 GMT September 2nd 1998

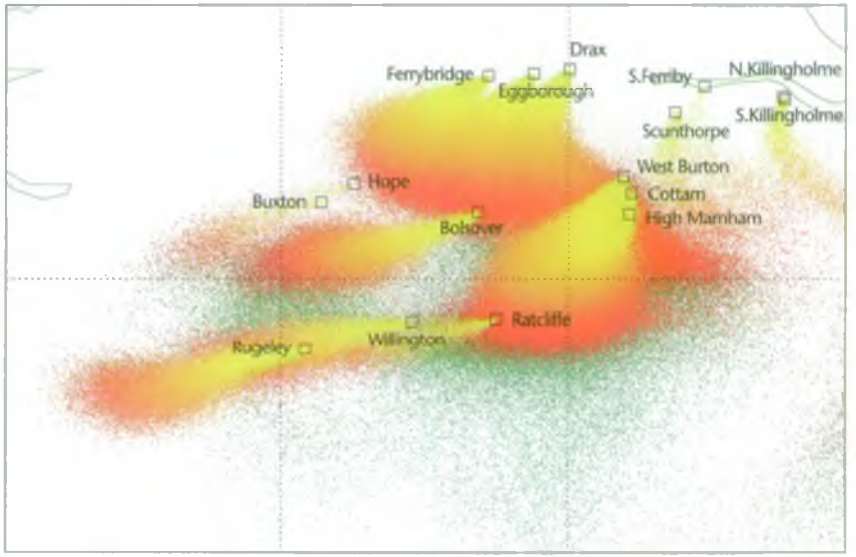
1 hour mean concentration



Instantaneous plume: boundary layer particles

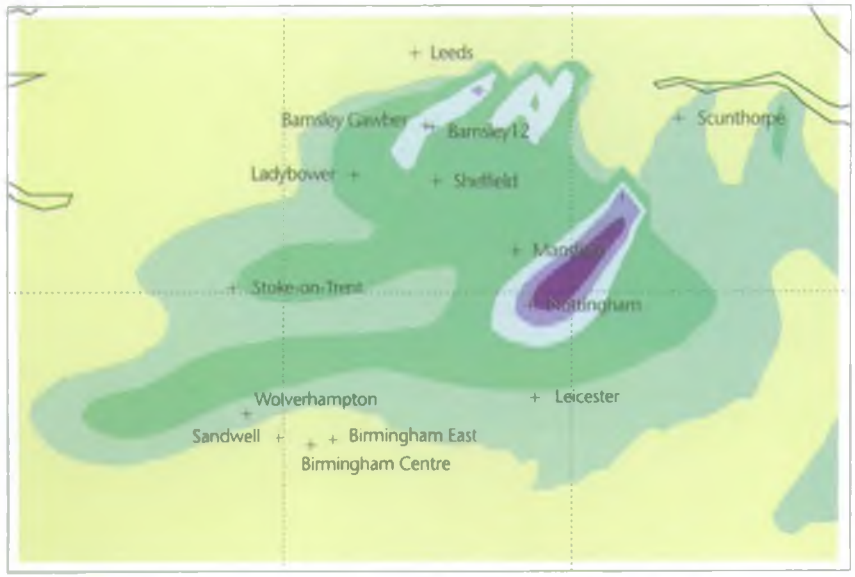


15:00 GMT September 2nd 1998

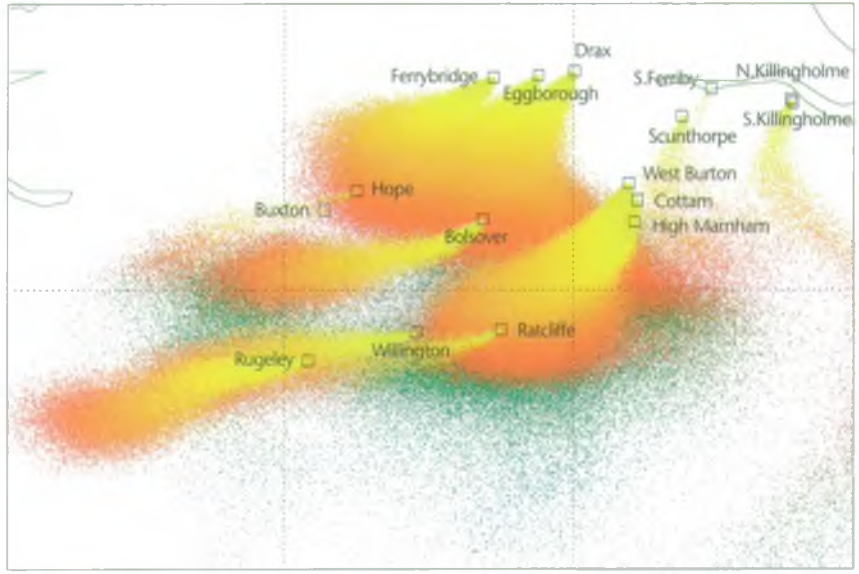


16:00 GMT September 2nd 1998

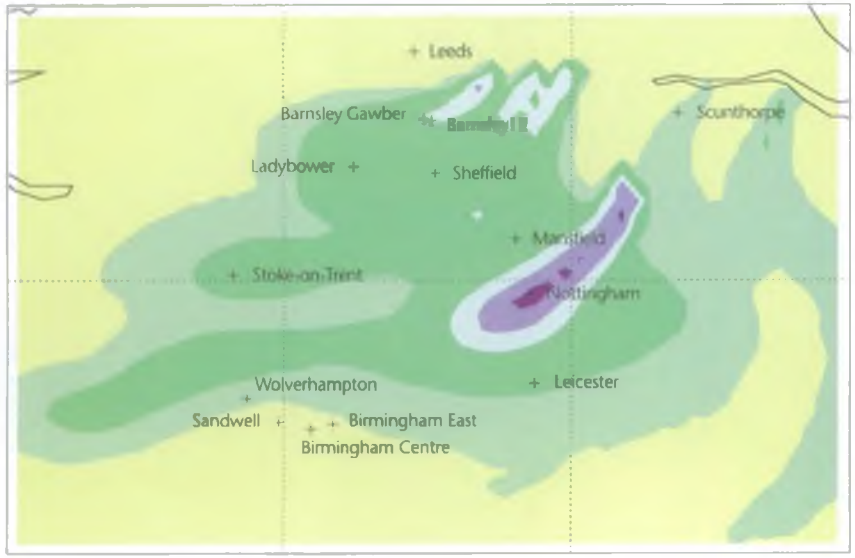
1 hour mean concentration

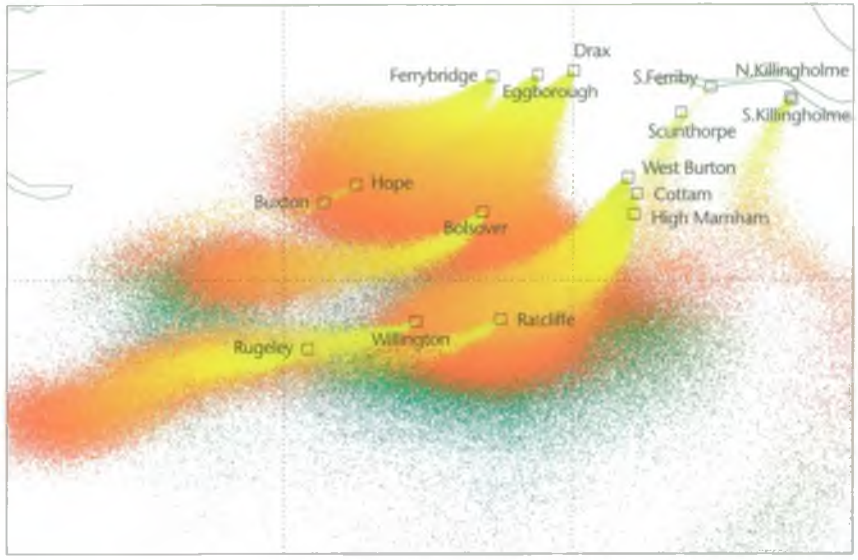


Instantaneous plume: boundary layer particles



17:00 GMT September 2nd 1998

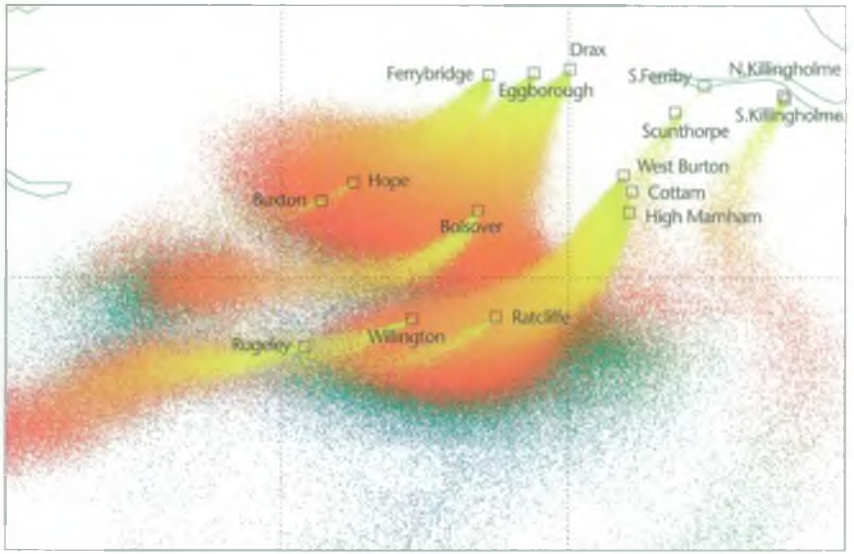




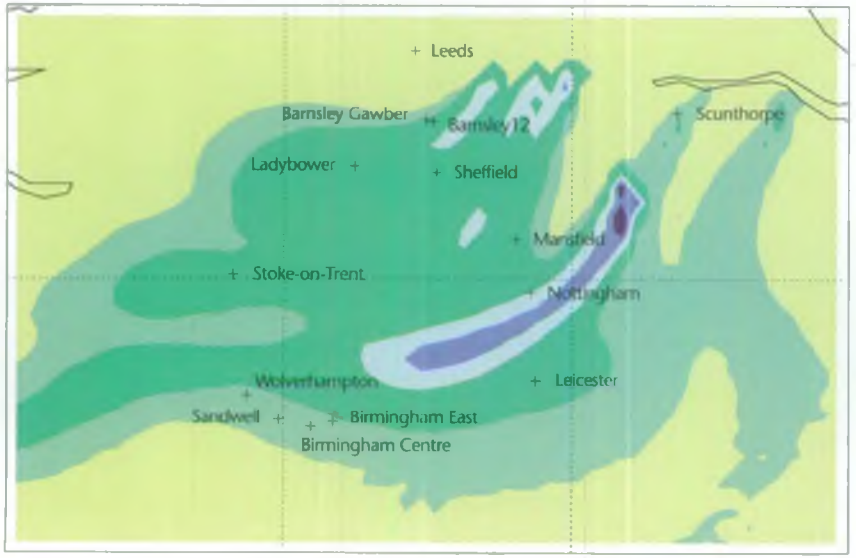
18:00 GMT September 2nd 1998

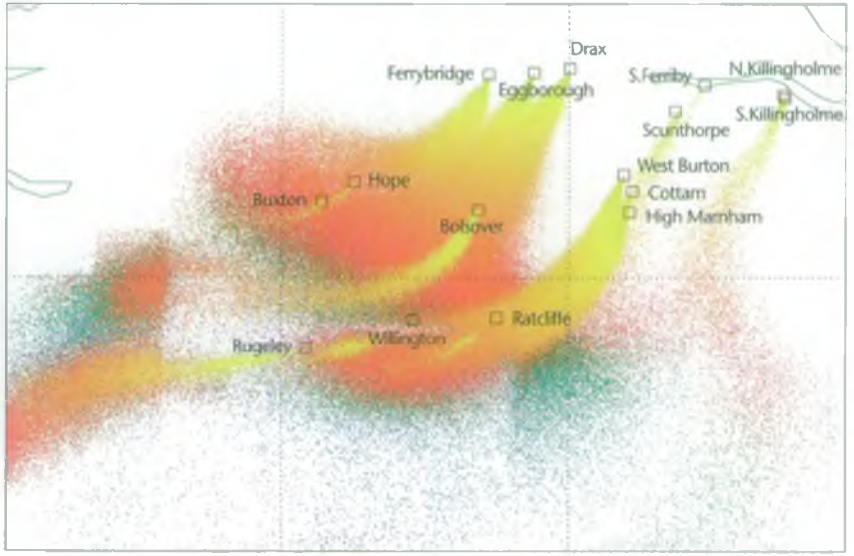
1 hour mean concentration

Instantaneous plume: boundary layer particles



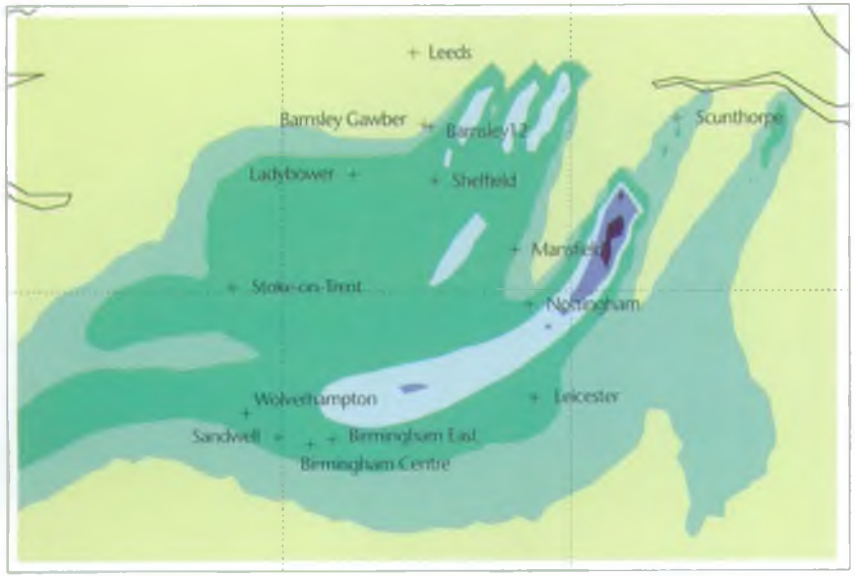
19:00 GMT September 2nd 1998



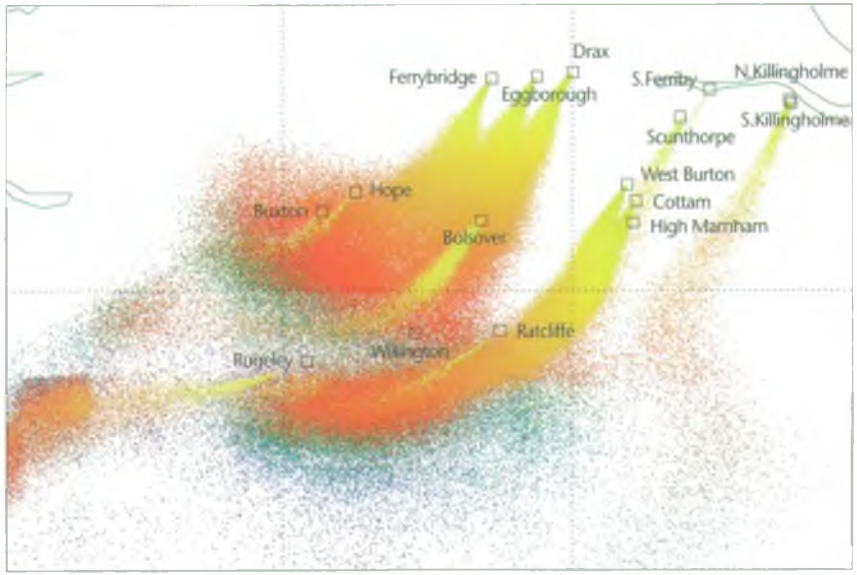


20:00 GMT September 2nd 1998

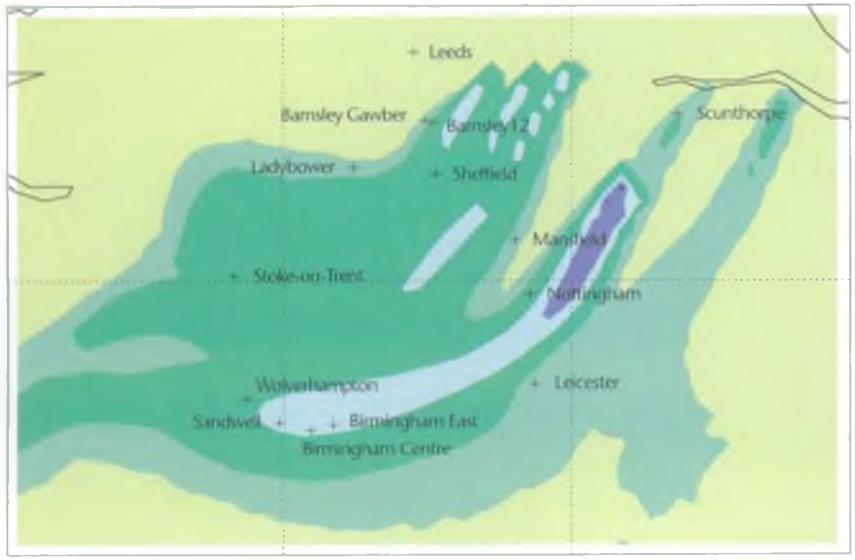
1 hour mean concentration

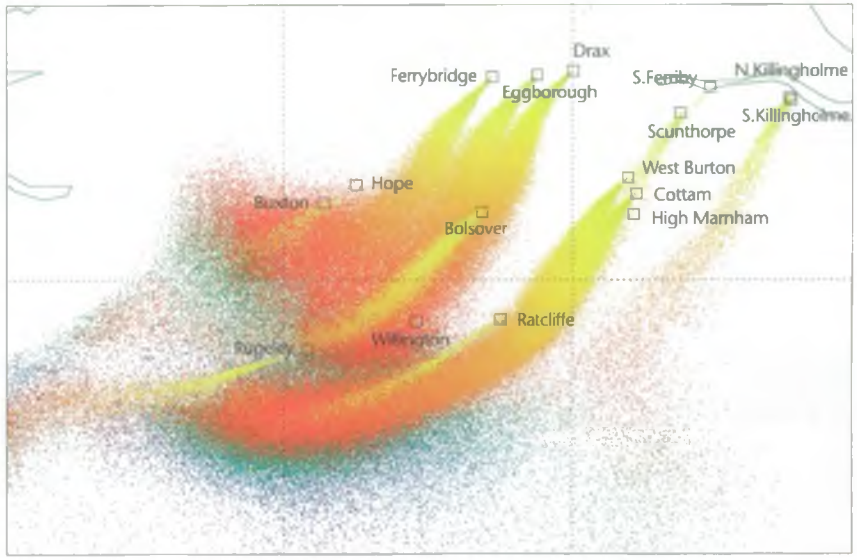


Instantaneous plume: boundary layer particles



21:00 GMT September 2nd 1998

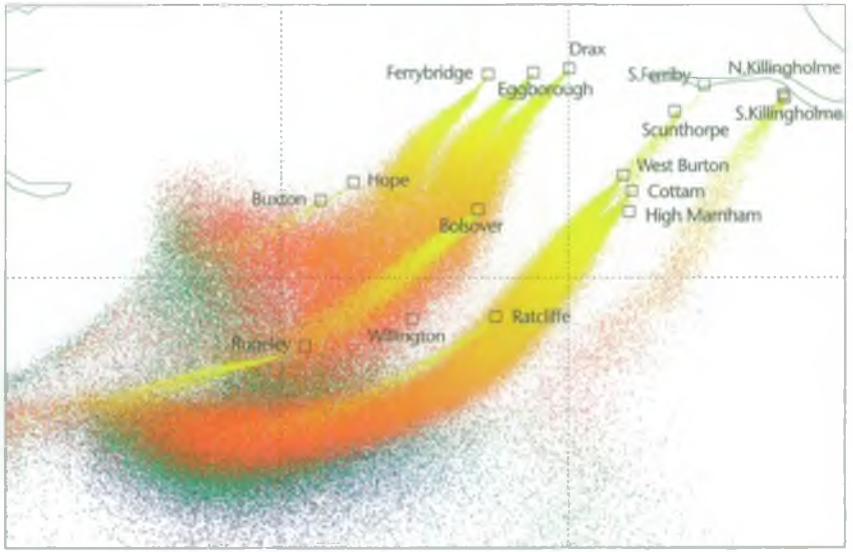




22:00 GMT September 2nd 1998

1 hour mean concentration

Instantaneous plume: boundary layer particles



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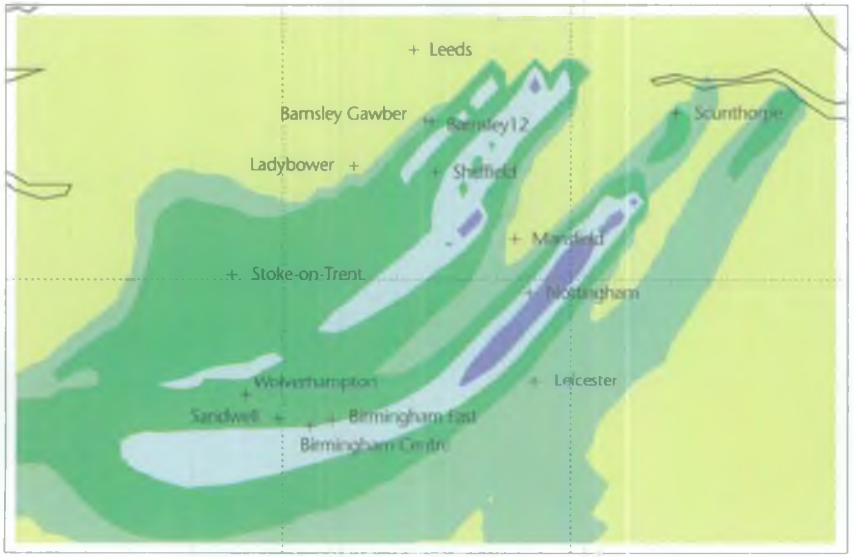
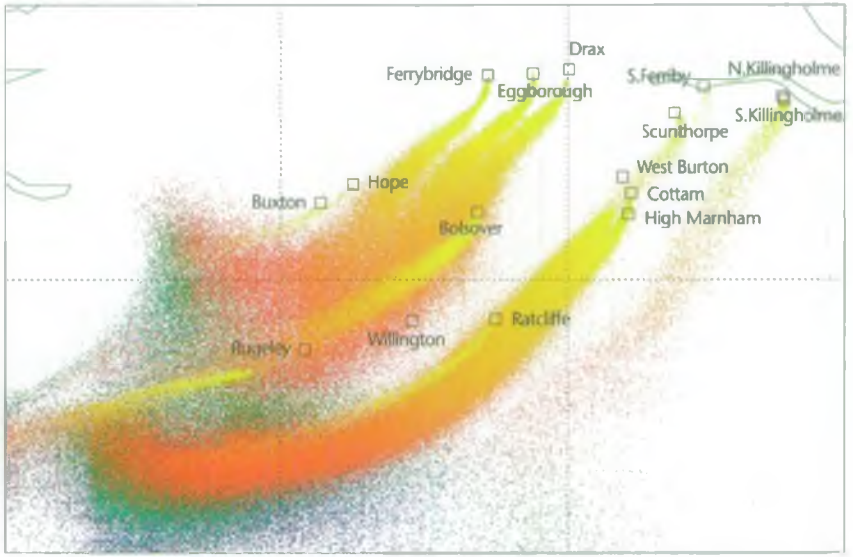


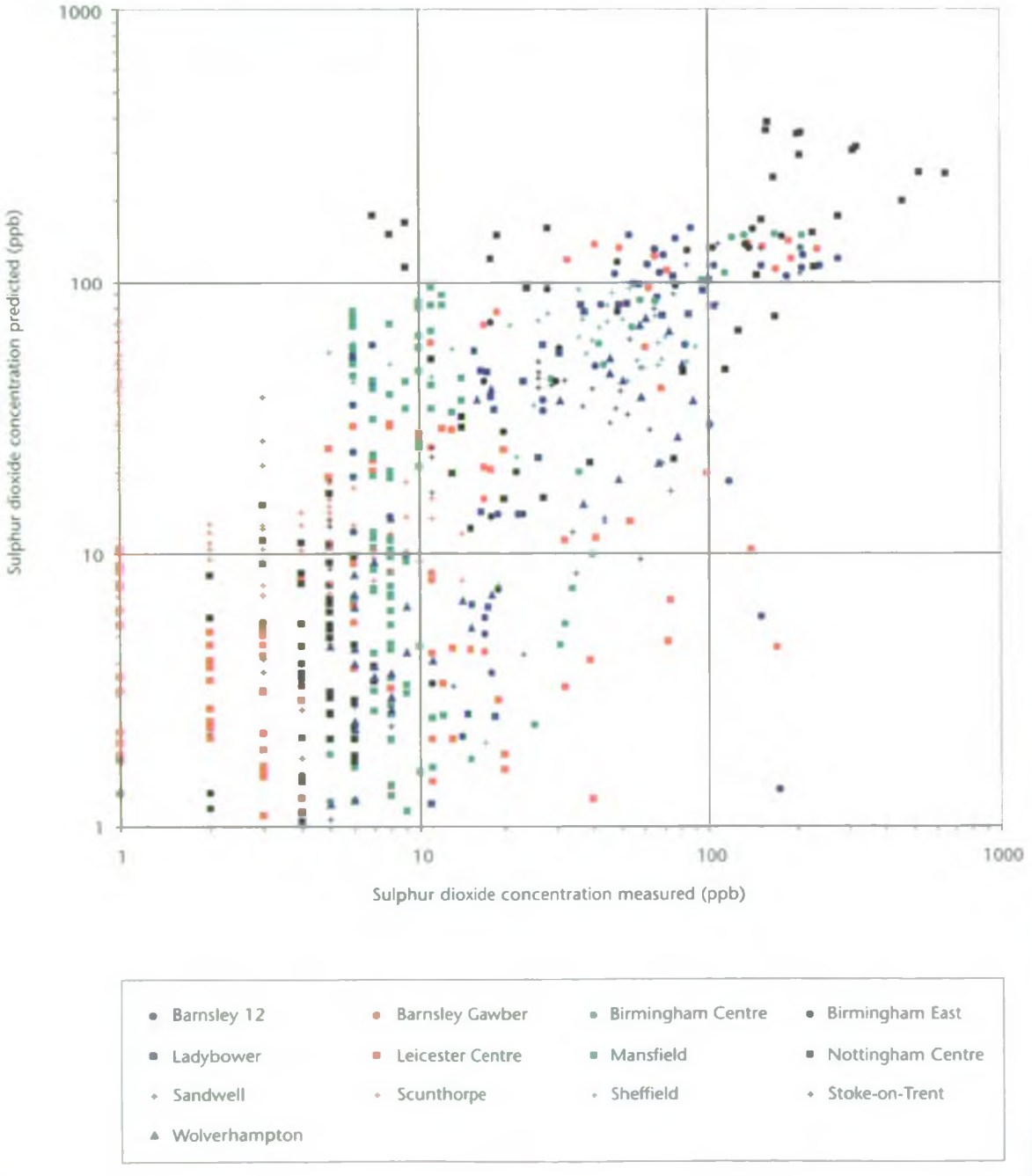


NAME performance analysis

To try to summarise the overall performance of NAME in predicting the concentrations measured at each monitoring station, the non-zero results for which monitoring data is available have been analysed in a variety of ways. This analysis is provided to allow the comparison with the performance of other air dispersion models, albeit using differing data sets.

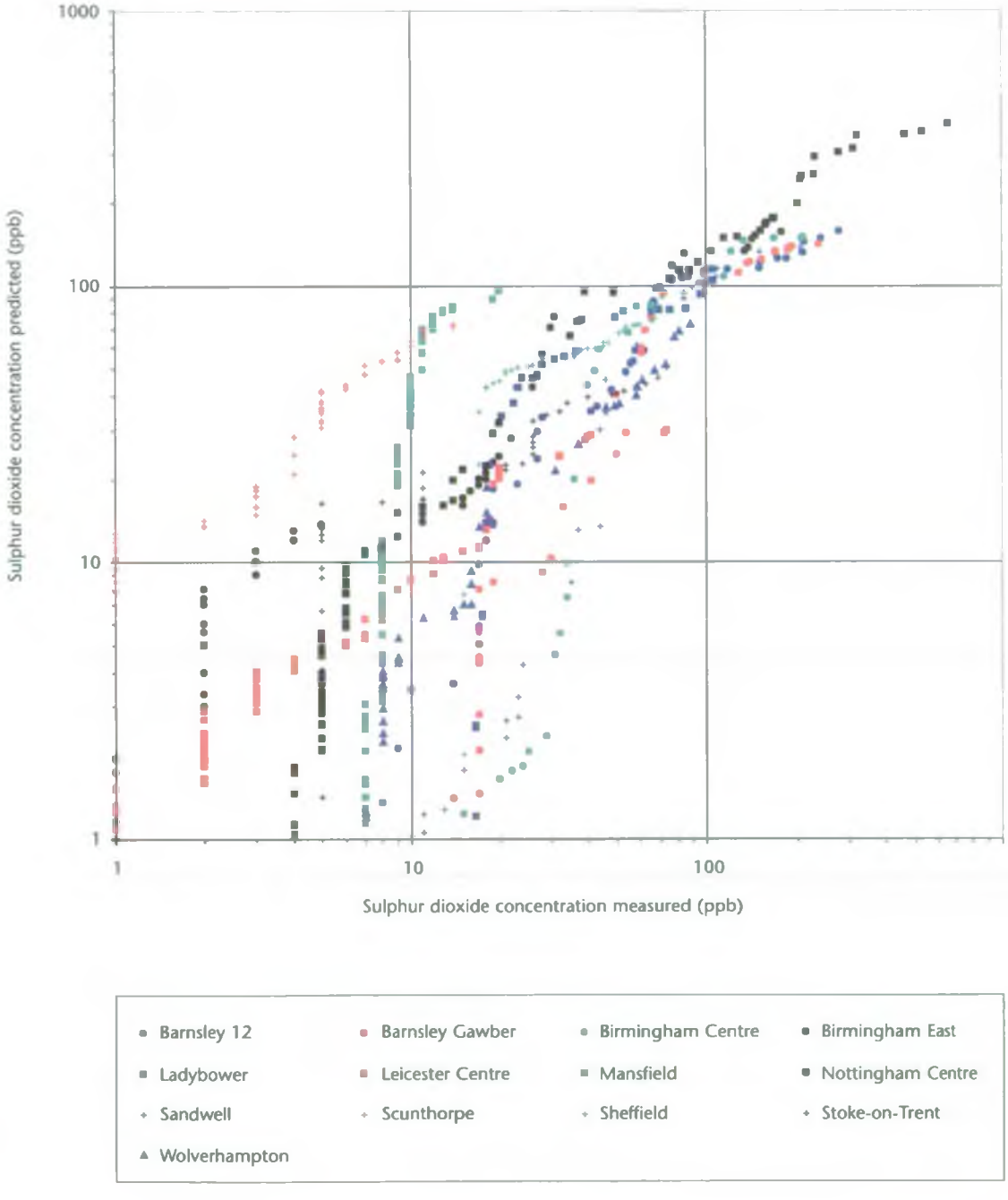
1. A **concentration scatter plot** where a measured concentration is plotted against the predicted concentration for exactly the same station and time. The CD-ROM contains the data used to generate this plot in a spreadsheet. The spreadsheet also contains individual scatter plots for each monitoring station.

Figure A7.38 Scatter plot for all monitoring stations



2. A **concentration quantile-quantile** plot where the measured and predicted concentrations are each ranked into descending order, the highest ranked measured is plotted against the highest ranked predicted, irrespective of whether they occurred at the same time. Similarly, the second highest pair is plotted and so on through the list of ranked measurements and predictions. The quantile-quantile plot therefore effectively removes the effect of time from the scatter diagram. The CD-ROM contains the data used to generate this plot. The spreadsheet also contains individual quantile-quantile plots for each monitoring station.

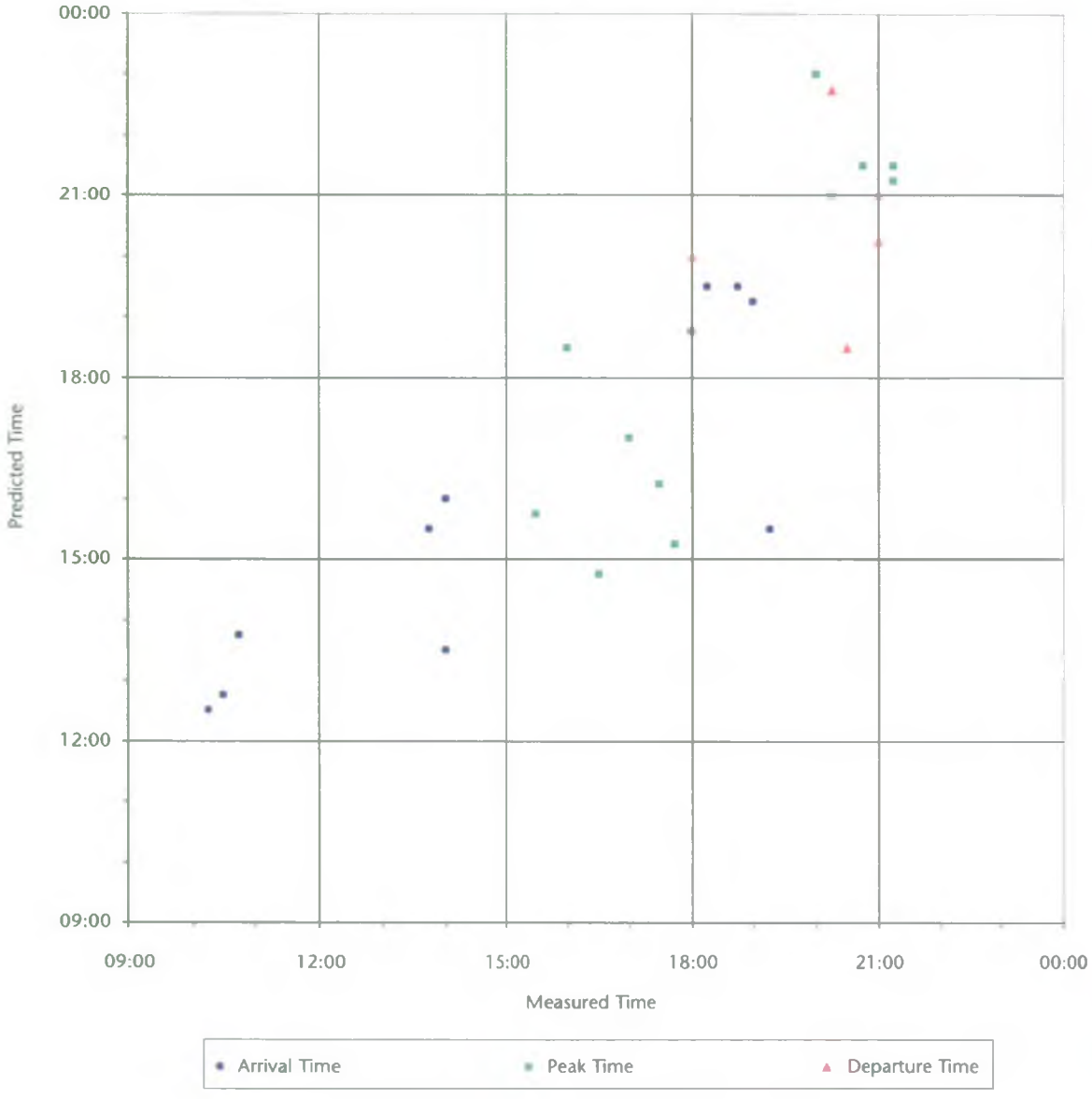
Figure A7.39 Quantile-Quantile plot for all monitoring stations



AVII

3. A **scatter plot of the arrival time** (the time when the concentration first rose above 10 ppb), the peak time, and the departure time (the time when the concentration eventually fell below 11 ppb). These concentrations were set arbitrarily. The scatter plot of timing therefore entirely removes comparison of concentrations.

Figure A7.40 Scatter plot of arrival, peak and departure time



4. **Statistical performance measures**

The following calculations were made to provide some statistical performance measure. These performance measures tend to equally weight all of the data. They have been calculated for the full set of non-zero data points.

FAC2	Fraction of predictions within a factor of two of the observations	
FB	Fractional Bias	$(\langle C_o \rangle - \langle C_p \rangle) / (0.5 (\langle C_o \rangle + \langle C_p \rangle))$
NMSE	Normalised Mean Square Error	$\langle (C_o - C_p)^2 \rangle / (\langle C_o \rangle \langle C_p \rangle)$
MG	Geometric Mean	$\exp (\langle \ln(C_o / C_p) \rangle)$
VG	Geometric Variance	$\exp (\langle (\ln(C_o / C_p))^2 \rangle)$

Where Co and Cp are the observed (measured) and predicted concentrations respectively.
And <...> indicates an average over all the data in a group.

Both FB and MG deal with mean biases, an ideal model has FB = 0, and MG = 1; FB uses arithmetic concentrations whereas MG uses the log of the concentration. NMSE and VG both deal with variances or scatter, and an ideal model has NMSE = 0, and VG = 1.

These calculations have been made for each monitoring station where 15-minute mean data was collected and predictions made by NAME. The median performance measures for the 12 monitoring stations in the statistical comparisons are:

FAC2	0.47
FB	0.07
NMSE	1.8
MG	1.1
VG	5.9

Comparison with the performance of other models is difficult because few performance measures have been published for this type of comparison. A recent published comparison of ADMS and AERMOD (see Section 5) for 5 sets of measurement data reported the median values as follows:

	ADMS	AERMOD
FAC2	0.53	0.46
MG	1.2	1.7
VG	2.4	2.9

These comparisons are subject to considerable interpretation as the model technologies are and data sets used are entirely different. What it does indicate is that for this Episode analysis, NAME performed on a par with other currently used atmospheric dispersion models.

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