REPORT

Initial review of Air Quality aspects of the Buncefield Oil Depot Explosion

A report produced for the Department for Environment, Food and Rural Affairs, the Scottish Executive, the Welsh Assembly Government and the Department of the Environment in Northern Ireland

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Front cover image by Dave Madle, Netcen

The Buncefield plume photographed from the air – © Chiltern Air Support Unit.

Executive Summary

On Sunday 11th December 2005, there was a major explosion at the Buncefield oil depot near Hemel Hempstead, north of London. Following the explosion, large stocks of refined product including petrol, aviation turbine fuel, diesel and gas oil at the depot remained on fire until Wednesday 14th December, when the last major fires were finally extinguished. A number of smaller fires continued until Thursday 15th December.

The large plume of particles and other pollutants produced by the fires could be seen from many kilometres away, and was also clearly identified in satellite images.

Netcen has estimated that 8,000 tonnes of PM_{10} particles may have been released during the fire; this is equivalent to approximately 6% of the total annual emissions of this pollutant in the UK (based on 2003 figures from the UK National Atmospheric Emissions Inventory).

This report aims to present and summarise the air quality measurements made during the Buncefield event. It includes results obtained from targeted local monitoring undertaken in and around the plant; this was organised by Defra, Netcen, the Health Protection Agency, the Hertfordshire Fire Brigade and the Met Office. The report also includes measurements from long-term monitoring networks supported by Department for Environment, Food and Rural Affairs (Defra), Devolved Administrations (DAs) and Local Authorities in the southeast of England.

The wide range of pollutants measured and reported here includes particulate matter (PM_{10}, $PM_{2.5}$ and PM_1, particles with a mean aerodynamic diameter of 10 μm, 2.5 μm and 1 μm, respectively), nitrogen oxides (NO_x), carbon monoxide (CO), volatile organic compounds (VOCs), dioxins, furans, hydrocarbons and polycyclic aromatic hydrocarbons (PAHs).

These air quality measurements are supported by modelling studies undertaken by the Met Office; these used atmospheric dispersion models to predict the transport and spread of the plume and to identify the origin of the air contributing to peak measurements. The Met Office carried out a variety of modelling studies during the event; these have subsequently been refined to take into account additional information and estimates of the plume's properties. These current best modelling analyses of the worst-case scenario (all fuel on site burnt) are summarised in Section 6 and examined in detail in Appendix E.

Localised monitoring of particulate matter and VOCs carried out in and around the depot showed that concentrations were elevated when compared to those recorded at nearby monitoring stations, but not markedly.

Likewise, provisional monitoring data from the UK's Automatic Urban and Rural Network (AURN), together with other regional networks in southeast England, did not show any significant increase in ground-level air pollution during the event. With the exception of a few localised and relatively unexceptional peaks, air pollution levels remained low everywhere.

Measurements taken from within the plume by the Facility for Airborne Atmospheric Measurements (FAAM) BAe146-301 research aircraft, operated by the Met Office and Natural Environment Research Council (NERC), showed that the plume was mainly black carbon- soot.

Despite the unprecedented scale of the Buncefield explosion and fire, a wide range of air pollution monitoring undertaken before, during and after the event showed that ground-level concentrations of a range of pollutants remained low to moderate over local, regional and national scales. It appears that the high plume buoyancy and favourable meteorological conditions resulted in the plume being trapped aloft, with minimal mixing to the ground. As a result, there are unlikely to have been widespread air quality impacts at ground level due to the pollutants emitted from the Buncefield fires.

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Appendix E – Met Office Plume Modelling

Appendix F – Samples from London PAH network sites during the Buncefield fire

Appendix G – Further Analysis of samples from London PAH network sites during the Buncefield fire

1 Introduction

At approximately 6:03 am on Sunday 11th December 2005, there was a major explosion and subsequent large-scale fires at the Buncefield oil depot near Hemel Hempstead (see Figure 1.1). This depot is a major distribution terminal storing refined oil and petrol, as well as kerosene supplies for airports across the region, including Heathrow and Luton. The force of the blasts was heard up to 40 miles away and flames rose more than 60 metres into the sky.

By midday on Monday 12th, the fires had been extinguished in 10 out of the 20 tanks affected by the blast. The last of the fires were extinguished on Thursday.

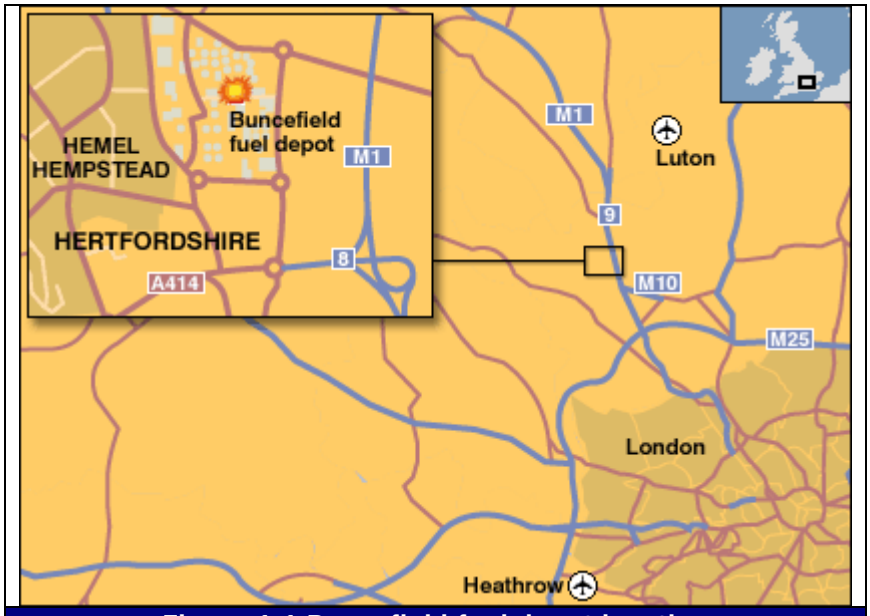

Figure 1.1 Buncefield fuel depot location
(image from www.bbc.co.uk)

Due to the large scale of the fires and the extensive black smoke plume, independent experts and the media expressed some concern about potential air quality impacts on public health, both in the vicinity of the depot and throughout southern England.

Air quality monitoring and forecasting across the UK, and in particular southeast England, continued as usual with no interruptions. The Automatic Urban and Rural Network (AURN), together with other local networks and monitoring stations in the region, provided valuable information on the impacts and effects of the fire. In fact, hour-by-hour updates on air quality at a range of locations throughout southern England were available throughout the event and its aftermath at the UK's national air quality website at www.airquality.co.uk .

On behalf of Defra and the Devolved Administrations, Netcen also carried out local air quality monitoring around the depot. Sampling was undertaken at a range of locations, both near the depot itself and in the surrounding areas, between December 12th and 14th. When selecting sampling points, the monitoring team attempted each day to target areas of maximum visible impact of the plume.

The Facility for Airborne Atmospheric Measurements (FAAM) BAe146-301 aircraft operated by the Met office and NERC also made detailed *in-situ* observations of the plume on the 13th December.

This report summarises currently available air quality measurements made before, during and after the fires, as well as the results of plume dispersion modelling carried out by the Met Office.

It includes the following sections:

- Timeline of events **(Section 2)**
- Emissions estimates **(Section 3)**
- Network monitoring data, targeted local air quality monitoring and aircraft measurements from within the plume **(Section 4)**

  Pollutants covered include:

  - PM_{10}, $PM_{2.5}$ and PM_1- particles of mean aerodynamic diameter of 10, 2.5 and 1 μm (micrometers), respectively
  - Nitrogen oxides- NO_x
  - Volatile Organic Compounds –VOCs
  - Dioxins and furans
  - Polychlorinated Biphenyls- PCBs
  - Hydrocarbons and Polycyclic Aromatic Hydrocarbons (PAHs).
- Air mass trajectory analysis **(Section 5)**
- Met Office modelling of the plume **(Section 6)**
- Conclusions **(Section 7)**.

An extended series of Appendices provide more detailed insight, measurements and analyses.

2 Timeline of Events

A detailed timeline of the events during the period of the fire from 6:03 am on Sunday 11th until the end of Wednesday 14th December is presented in Figure 2.1. See also Appendix H.

The explosion occurred at 6:03 am, after which the plume rose very rapidly due the high buoyancy generated by the heat of the fire. The plume penetrated the temperature inversion at the top of boundary layer (the lowest part of the atmosphere which is directly influenced by the earth's surface) and was transported into the stable atmosphere above, reaching a height of around 3000m. There was significant wind shear, with north-westerly winds at lower levels and northeasterly winds aloft. This resulted in a fan like appearance of the plume, as shown in Figure 2.2, which could readily be seen in MODIS (MODerate resolution Imaging Spectroradiometer) satellite imagery obtained from NASA's Terra and Aqua satellites.

The anticyclonic conditions of the day resulted in a stable atmosphere; as a result, there was little mixing within the boundary layer, with most of the plume transport occurring in the free troposphere.

During the morning of Monday 12th December, a weak frontal system moved through the area. Following the clearance of the front, there were north-easterly winds at all levels over the source. These resulting in a narrow plume being transported towards the south-west, as shown by the MODIS image from the Aqua satellite at 12:40 pm (Figure 2.3).

On Tuesday 13th December there was considerably more cloud, which reduced the availability of satellite imagery of the plume. The winds were north/north-easterly, resulting in the plume being advected south. The plume was intercepted by the FAAM aircraft, which was able to confirm that the Met Office NAME model forecasts of the plume's position were correct. From Tuesday 13th to Wednesday 14th December, the winds backed round to more northerly.

By Thursday 15th December, only small fires remained at the site. Winds became north-westerly and stronger. The remainder of the plume was therefore transported to the south-east and rapidly dispersed in the moderate winds.

Figure 2.4 illustrates the different plume locations identified by satellite imagery and aircraft observations. Starting from the satellite picture obtained at 11:50 am on 11th December, the increased dispersion is shown by the area delimited by a black line (plume dispersion at 1:35 pm on 11th). The transport of the plume on 12th and 13th December was more linear. The other three lines represent this:

- Blue: at 10:00 am on 12th December
- Purple: at 12:10 pm on 12th December, and
- Green: between 12:00–1:00 pm on 13th December

Full details of the plume positioning over the period is given in Section 6 and Appendix E, which detail Met Office NAME modelling of the event.

During the fires, national air quality monitoring and daily forecasting of air quality were carried out as usual, with a duty air quality forecaster at Netcen undertaking checks on monitoring data from the AURN and other air quality monitoring networks. The 24-hour forecasting updates at 3:00 pm (see Figure 2.5, Table 2.1 and Table 2.2) were complemented with a 9:00 am forecasting update. Close liaison with the Met Office's Environmental Monitoring and Response Centre (EMARC) was maintained during the event, in order to obtain up-to-date weather reports and the latest information on model predictions of the plume dispersion.

Air quality information in the form of hourly measurements from the AURN and forecasts were published as usual on the UK Air Quality Archive (www.airquality.co.uk) and on Teletext. Data from automatic monitors were published within an hour of measurements being taken[1]. The Air Quality Archive usage statistics show a great increase in public interest during the event (see Figure 2.6) Defra was regularly updated with the latest information. The public and the media were also informed through the Air Quality Archive online news and email bulletins, together with personal communications by the Air Quality Forecasting team.

[1] An hour is the usual time lag between a measurement being taken and published on the Internet. This is the inevitable result of the large number of monitoring sites in the network from which data have to be acquired.

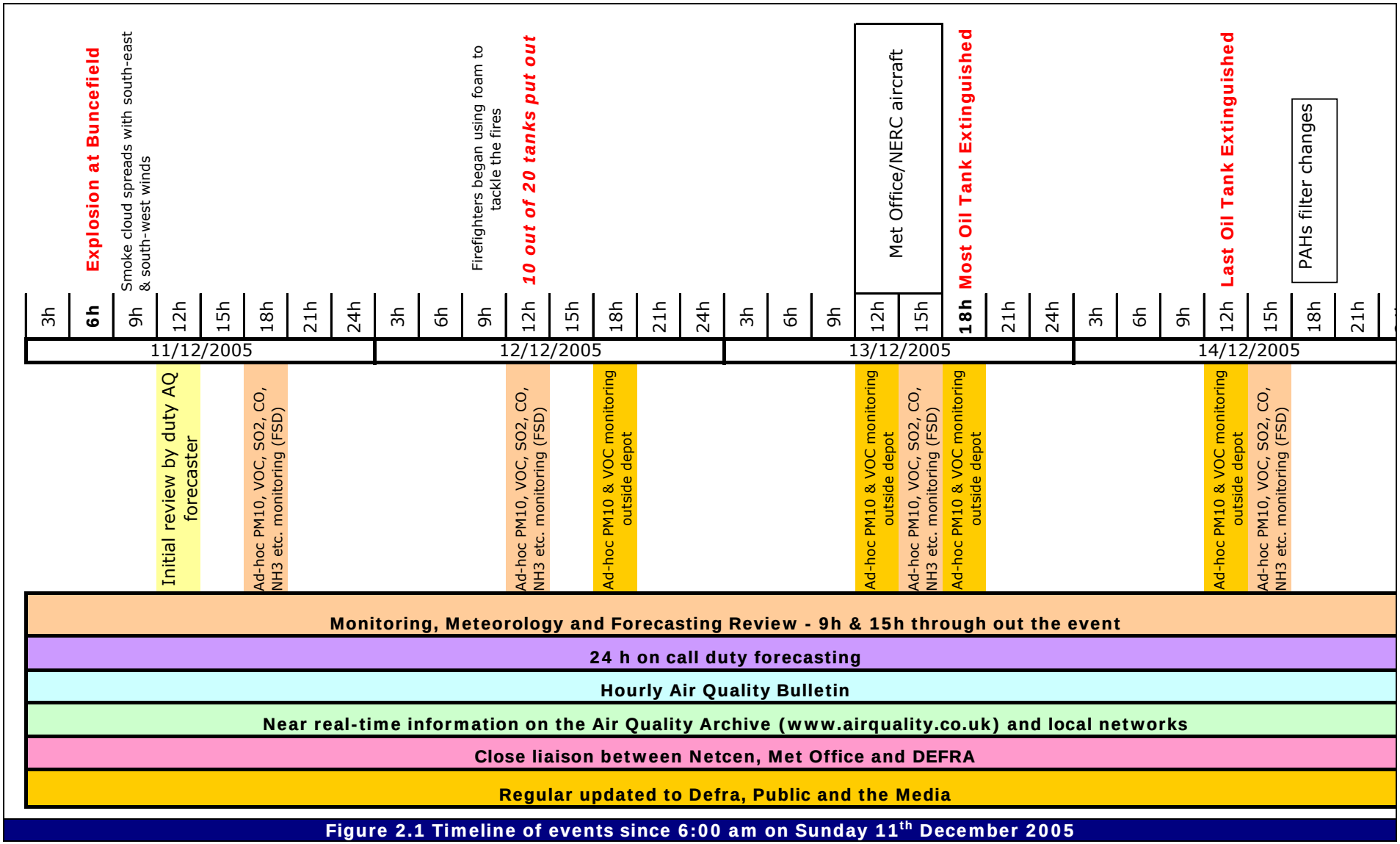

Figure 2.1 Timeline of events since 6:00 am on Sunday 11th December 2005

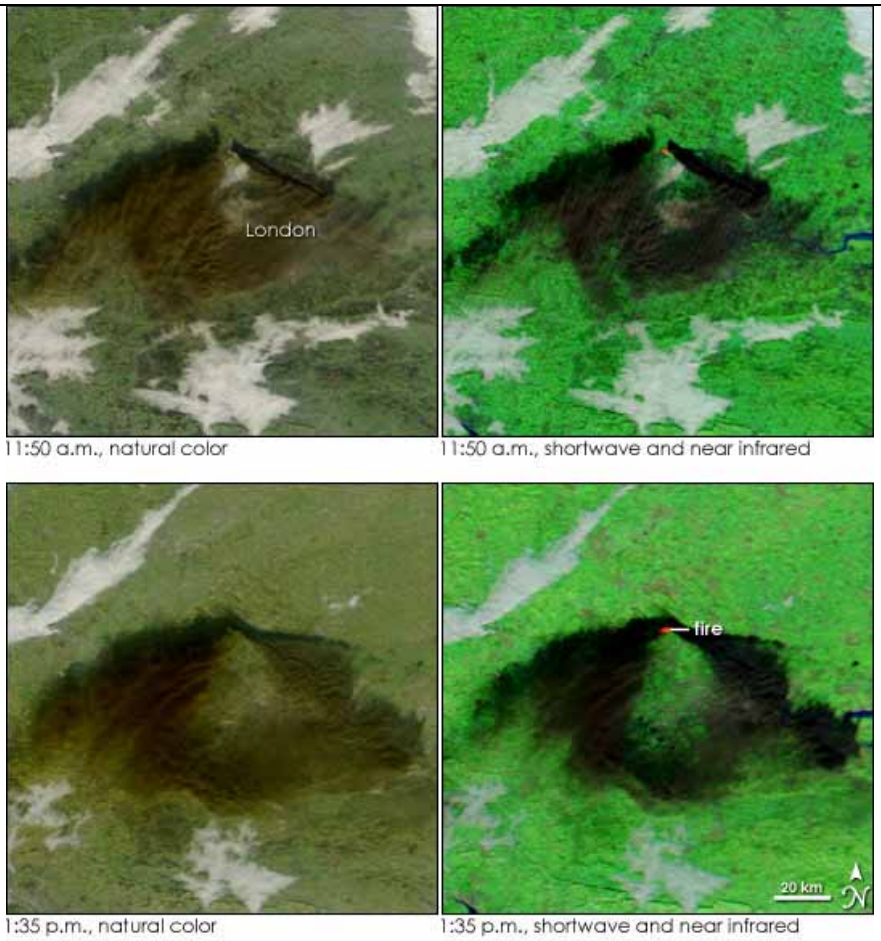

Figure 2.2 Satellite images on 11/12/05 (upper panel showing MODIS instrument images from the NASA Terra satellite, lower panel showing MODIS instrument images from the NASA Aqua satellite)

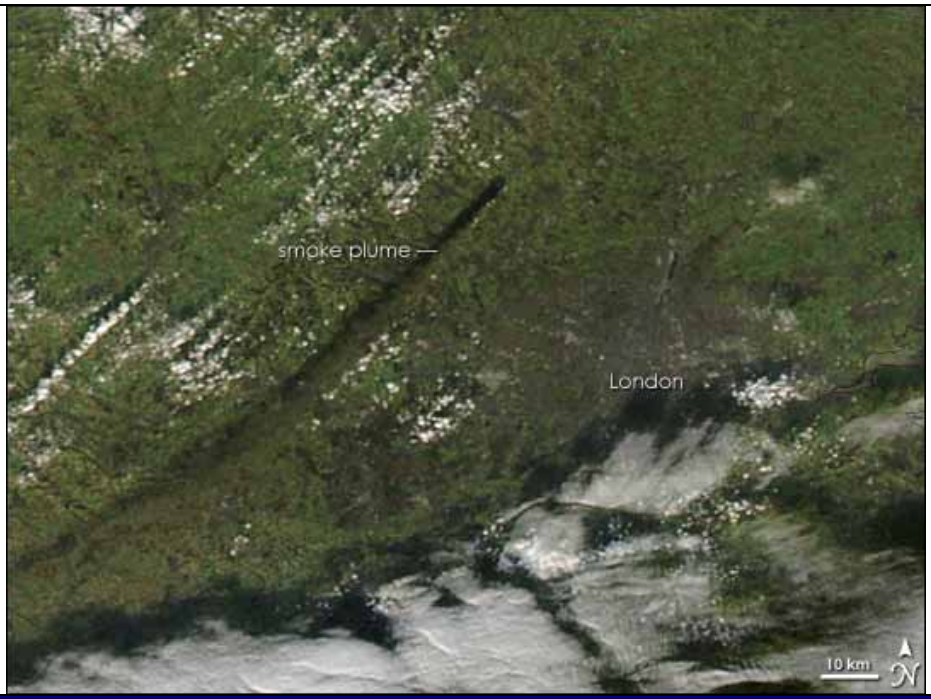

Figure 2.3 MODIS image captured by NASA's Aqua satellite at 12:40 pm local time on 12/12/05.

Images in Figures 2.2 and 2.3 courtesy of MODIS Rapid Response Project at NASA/GSFC

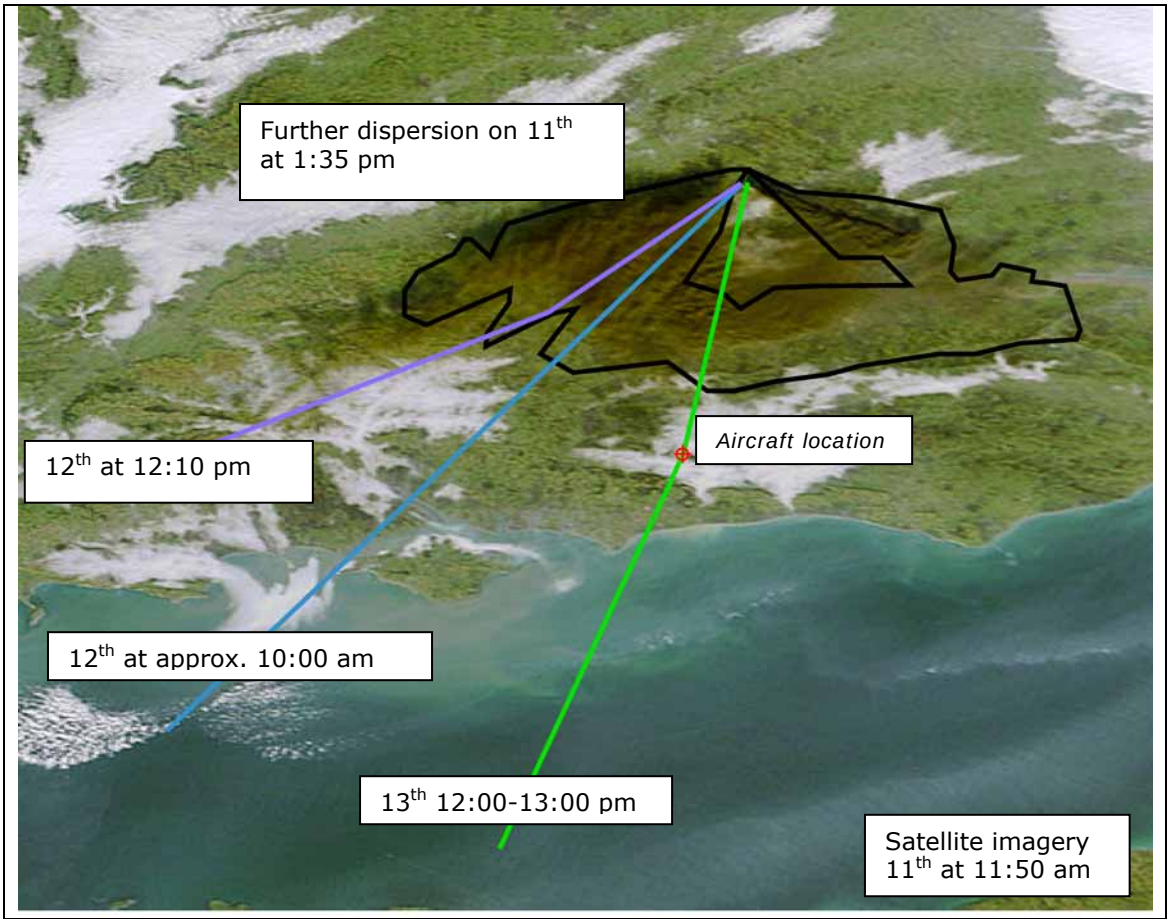

Figure 2.4 Changes of the plume between 11th and 13th from satellite and aircraft observations

Air Pollution is on a scale of 1 to 10

Low (1 - 3) Moderate (4 - 6) High(7 - 9) Very High (10)

About this scale

Click on any of the links below to see the relevant information

Measurements **Forecast** **Alerts**

Maximum Pollutant levels recorded for the 24 period hour up to 3pm Sun Dec 11th 2005					
N/M means that the pollutant is not measured at that site N/A means that no data were recorded for the period					
Greater London					
SITE	Hourly Mean Ozone (μgm^{-3})	Hourly Mean Nitrogen dioxide (μgm^{-3})	max 15min mean Sulphur dioxide (μgm^{-3})	8 Hourly Mean Carbon monoxide (mgm^{-3})	24Hour mean PM_{10} Particles (μgm^{-3}Grav Equiv)
A3 Roadside	N/M	117 (Low 2)	N/M	1 (Low 1)	52 (Low 3)
Bexley	8 (Low 1)	61 (Low 1)	11 (Low 1)	0.7 (Low 1)	40 (Low 2)
Bloomsbury	3 (Low 1)	99 (Low 2)	19 (Low 1)	1.1 (Low 1)	33 (Low 2)
Brent	2 (Low 1)	82 (Low 1)	13 (Low 1)	1.8 (Low 1)	41 (Low 2)
Brentford Roadside	N/M	134 (Low 2)	N/M	2.7 (Low 1)	N/M
Bromley	N/M	57 (Low 1)	N/M	N/A	N/M

...

Air Pollution Forecast

Air pollution forecast until 3pm Mon Dec 12th 2005

Region	In rural areas	In towns and cities away from busier roads	In towns and cities next to busier roads
North East	3 (Low)	2 (Low)	2 (Low)
North West & Merseyside	3 (Low)	2 (Low)	2 (Low)
Yorkshire & Humberside	3 (Low)	3 (Low)	3 (Low)
East Midlands	3 (Low)	2 (Low)	2 (Low)
West Midlands	3 (Low)	2 (Low)	2 (Low)
Eastern	3 (Low)	3 (Low)	3 (Low)
South East	4 (Moderate)	4 (Moderate)	4 (Moderate)
South West	3 (Low)	2 (Low)	2 (Low)
South Wales	3 (Low)	2 (Low)	2 (Low)
North Wales	3 (Low)	3 (Low)	3 (Low)
Scottish Borders	3 (Low)	3 (Low)	3 (Low)
Central Scotland	3 (Low)	2 (Low)	2 (Low)
North East Scotland	3 (Low)	2 (Low)	2 (Low)
Highland	3 (Low)	3 (Low)	3 (Low)
Northern Ireland	3 (Low)	3 (Low)	3 (Low)

Figure 2.5 Example of daily air pollution bulletin

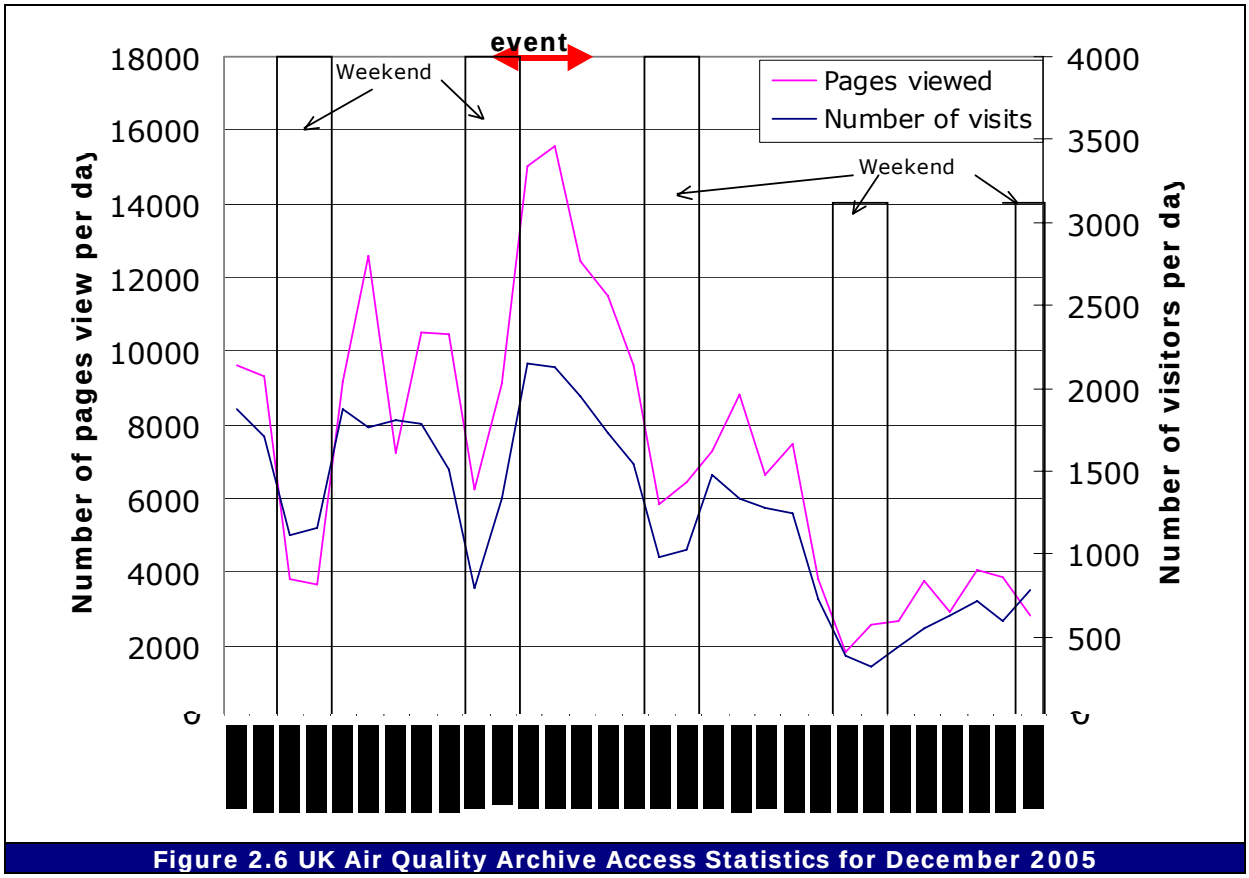

Figure 2.6 UK Air Quality Archive Access Statistics for December 2005

Table 2.1 Air quality forecasting email sent on Monday 12th December

From: Jaume Targa, Netcen To: Air Quality Forecast Recipients Subject: Air Quality Forecasting - BUNCEFIELD OIL DEPOT FIRE	12/12/2005 14:53:34

Dear Colleagues,

The national air quality monitoring network has not recorded any high levels of air pollution in Southern England following yesterday's fire at the Buncefield oil depot.

A High Pressure System is currently building up over the UK and will remain, at least, for the next 48 hours. At the moment, the plume has been buoyant enough to punch through the boundary layer. Hence, the lack of monitoring stations measuring moderate/high levels of air pollution.

As you can see from the NOAA picture attached from 11.53 on 12th December 2005, the plume is heading towards Southampton and Weymouth with no risk in grounding. All the pollution from the plume is still trapped above the boundary layer. We're continuing to liaise with the Met Office now and trying to forecast when/if it will ground.

At present, the only chances of pollution grounding are likely to be caused by changes in the buoyancy of the plume. If this does happen, localised pollution events near the depot may be expected.

As a cautionary approach, we have forecast MODERATE levels across Greater London, Eastern and the South East zones.

Yours,

Jaume Targa
Netcen

Table 2.2 Air quality forecasting email on Tuesday 13th

From: Jaume Targa, Netcen To: Air Quality Forecast Recipients Subject: Air Quality Forecasting - BUNCEFIELD OIL DEPOT FIRE	13/12/2005 14:54:00

Dear Colleagues,

The national air quality monitoring network has still not recorded any high levels of air pollution in the UK following Sunday's fire at the Buncefield oil depot (www.airquality.co.uk).

The High Pressure System over the UK will remain until the end of today. It will be moving towards the Atlantic and a Low Pressure System will be established over the UK by Friday. The weather will remain dry with bright spells for central and eastern areas. Some light showers might be experienced tomorrow, but first heavy rain is expected on Friday. Wind direction is currently north-westerly changing northerly tomorrow.

The plume has been moving towards the south changing to the southeast over the afternoon. This will remain until tomorrow when the winds change again.

Up to now, the plume has kept buoyant enough to penetrate the boundary layer. However, as the fire is put out, the plume might become less buoyant and localised pollution might be measured. The area of risk due to localised pollution is likely to be towards the southeast of the oil depot. Any important regional-transboundary pollution is unlikely, as the plume is dispersing well with high wind speeds above the boundary layer.

At present, the atmospheric conditions are neutral/ stable with some mixing from above the boundary layer. This is unlikely to cause any important pollution event.

Any pollution event is likely to be caused by changes in the buoyancy of the plume. If this does happen, localised impacts near the depot are expected (South-East of the depot).

As a cautionary approach, we have forecast MODERATE levels across Greater London, Eastern and the South East zones. HIGH levels of pollution might arise near the depot.

Yours,

Jaume Targa
Netcen

PS: The current high PM10 levels at Bradford Centre are unrelated to Sunday's event. This is due to localised emissions from construction near to the air quality monitoring site.

3 Estimates of possible emissions

Netcen has estimated the total air pollutant emissions to the atmosphere from the oil fire, both during and after the event. These calculations were useful in order to 1) enable improved modelling of the plume and 2) understand the potential air quality impact of pollutants emitted during the fires.

The total amount of fuel at Buncefield Oil Depot was estimated from information about the terminal capacity provided by the UK Petroleum Industry Association (UKPIA) and Total. Complete information on the actual quantities of fuel at the terminal during the event is not available at this time. These figures are therefore provisional and may need to be revised as more definitive information is made available.

Table 3.1 shows our current best information on the types of fuel, together with an estimate of the total tonnage of each type that was stored at the depot. The initial estimate of the total volume of fuel on site was 105 million litres (82359 tonnes).

Table 3.1 – Estimates of the total fuel (tonnes) at Buncefield oil depot

Terminal*	Fuel[1]	Volume, million litres	Litres per tonne [2]	Tonnes
HOSL	Petrol	35	*1362*	**25698**
HOSL	Petrol	1.7	*1361*	**1267**
HOSL	Burning	18	*1248*	**14423**
HOSL	Aviation turbine fuel	0	-	**0**
HOSL	DERV (diesel)	15.8	*1203*	**13113**
HOSL	Gas oil	6.5	*1187*	**5476**
BPA	Aviation turbine fuel	28	*1251*	**22382**
	Total estimate	**105**	**-**	**82359**

* Hertfordshire Oil Storage Terminal (HOSL) & British Pipeline Agency (BPA)

Pollutant emission factors from the UK National Atmospheric Emission Inventory (NAEI at www.naei.org.uk[3]), together with other published sources, were used to estimate the total emissions arising from the fire at Buncefield oil depot. The quantities of air pollutants emitted were estimated for four possible scenarios for the event:

1) 90% of fuel from BPA and 60% of fuel from HOSL lost[4]
2) LOW estimate (50% loss of fuel on site assumed)
3) MEDIUM estimate (75% loss of fuel on site assumed)
4) HIGH estimate (100% loss of fuel on site assumed)

These scenarios attempt to give a picture of the different possible outcomes of the fire, including a more realistic scenario (1) as well as a possible worst-case scenario (4). At the time of writing this report, clear information of the actual quantity of fuel consumed in the blaze is not yet available.

The pollutants selected have air quality standards/objectives (or proposed standards/objectives), are greenhouse gas/global warming pollutants, or were considered to be most relevant for public

[1] Fuel types are as used in the UK National Atmospheric Emission Inventory
[2] From the Digest of UK Energy Statistics (DUKES) available at: http://www.dti.gov.uk/energy/inform/dukes/dukes2005/annexa.pdf
[3] http://www.naei.org.uk/reports.php
[4] The HOSL inventory is for both the West & East sections of the terminal. The West terminal was most affected by the fire, while the tanks in the East section remained intact.

health concern. An important factor considered, also, was whether any relevant emission factor data (on pollutants emitted per mass unit of fuel combusted) was available.

The pollutant emissions estimated are as follows:

- Nitrogen dioxide (NO_2) – A UK air quality strategy pollutant
- Particulate matter of mean aerodynamic diameter 10 µm (PM_{10}) – Air quality strategy pollutant
- Particulate matter of mean aerodynamic diameter 2.5 µm ($PM_{2.5}$) – Proposed air quality strategy pollutant.
- Dioxins – persistent organic pollutant
- Benzo(a)pyrene (B[a]P) - Proposed air quality strategy pollutant and polyclyclic aromatic hydrocarbon (PAH) indicator.
- Carbon monoxide (CO) – Air quality strategy pollutant
- Non-methane volatile organic compounds (NMVOC) – ground level ozone precursors
- Benzene – air quality strategy pollutant
- Carbon dioxide (CO_2)– greenhouse gas

Emission estimates were calculated for each scenario by multiplying the quantity of fuel burnt by a pollutant emission factor. In general, emission factors have been applied for 'open-burning' of oil fires. The factors used were obtained from a number of sources and are summarised in Table 3.2. Table 3.3 shows the amount of pollutants emitted and their percentages in relation to UK 2003 total emissions, as reported in the National Atmospheric Emissions Inventory (NAEI).

Table 3.2 Summary of pollutant emission factors

Pollutant	Emission factor, mg/kg	Source and comment
Nitrogen oxides	651	Derived from Lemieux et al CO emission factor and ratio of NO_X to CO reported by Evans et al
PM_{10}	170000	Lemieux et al and US Dept of Defence range of PM_{10} in total PM
$PM_{2.5}$	102000	From 60% $PM_{3.5}$ figure of Ross et al.
Benzo(a)pyrene	5	Lemieux et al
Carbon monoxide	30000	Lemieux et al for crude oil
Non-methane volatile organic compounds	1770	Lemieux et al – sum of VOC and carbonyl compounds
Benzene	1022	Lemieux et al
	ng WHO-TEQ/kg[5]	
Dioxins and furans	2.31×10^{-5}	World Health Organisation toxic equivalent factors for mammals applied to Lemieux data for speciated dioxin and furan congener groups
References		
Lemieux, P.M. et al. Emissions of organic air toxics from open burning: a comprehensive review. Progress in Energy & Combustion Science, 30 (2004) 1-32		
Evans, D et al. Environmental effects of oil spill combustion. US Dept of Commerce, NIST, National Engineering Laboratory Centre for Fire Research, NISTIR 88-3822, Sept 1987		
Ross et al, Particle and Gas Emissions from an In Situ Burn of Crude Oil on the Ocean J. Air & Waste Manage. Assoc., 46, 251-259, 1996		
Oil fire health review by US Dept of Defence Deployment Health Clinical Centre		

Carbon dioxide and carbon emission factors are from the NAEI 2004 database. Particulate emissions from uncontrolled oil fires are largely unburnt fuel. CO_2 emissions in Table 3.3 have been modified to account for unburnt fuel in particulate (carbon content of PM estimated to be 95% based on typical fuel analysis and range of 92-100% 'elemental carbon' in oil fire smoke analysis).

[5] WHO-TEQ – there are many dioxin and furan congeners a number of which are considered hazardous to a greater or lesser extent. Use of toxic equivalence factors allows an assessment of the most significant congeners on a consistent basis. The toxic equivalence factors are published by the World Health Organisation.

The emission estimates indicate that PM_{10}, $PM_{2.5}$ and B[a]P emissions represented the greatest relative proportion of corresponding national emissions. Estimated PM_{10} and $PM_{2.5}$ emissions were between 4 to 8.5% of total UK annual emissions, while B[a]P emissions were between 5 and 10%. The emissions for other pollutants like NO_2 and dioxins would be around 40 tonnes and 1.5 *WHO-TeQ g*, (0.003% and 0.6% of total UK annual emissions, respectively).

Table 3.3 – Estimates of total emissions of air pollutants emitted from Buncefield oil fire

Pollutants	Scenario					UK Total (2003)		Scenario (%)			
	1	2	3	4	Units			1	2	3	4
NO_X	37.2	27.3	40.9	54.6	*Tonnes*	1570	*kTonne*	0.0024	0.0017	0.0026	0.0035
PM_{10}	8249.5	6054.8	9082.2	12109.6	*Tonnes*	141	*kTonne*	5.8507	4.2942	6.4413	8.5884
$PM_{2.5}$	4949.7	3632.9	5449.3	7265.7	*Tonnes*	86.9	*kTonne*	5.6958	4.1805	6.2708	8.3610
Dioxins	1.32	0.97	1.45	1.93	*g-TeQ g*	259	*g-TEQ g*	0.5087	0.3734	0.5601	0.7468
B[a]P	285.4	209.5	314.3	419.0	*kg*	4034	*kg*	7.0761	5.1936	7.7903	10.3871
CO	1712.7	1257.0	1885.6	2514.1	*Tonnes*	2768	*kTonne*	0.0619	0.0454	0.0681	0.0908
NMVOC	101.0	74.2	111.2	148.3	*Tonnes*	1089	*kTonne*	0.0093	0.0068	0.0102	0.0136
Benzene	58.3	42.8	64.2	85.6	*Tonnes*	13.6	*kTonne*	0.4290	0.3149	0.4723	0.6298
CO_2	0.144	0.105	0.158	0.211	*Mtonne*						
C	39.2	28.7	43.1	57.5	*kTonne*	152324	*kTonne*	0.026	0.019	0.028	0.038

There are a number of uncertainties associated with the emission estimates. These include:

- Uncertainty of emission factors and relevance of emission factors to the fuels and circumstances of the Buncefield fire. We note that there remains some uncertainty in the volume of fuel stored on site and therefore likely to have burnt. For example, the Buncefield Investigation progress report states that over 35 million litres of fuel was on site on 11/12/05 (Buncefield investigation team, 2006)[1].

- The emission factors used are from a variety of sources for uncontrolled burning, some of which may not be applicable to combustion of refined fuel products in pools.

- The range of emission factors for some pollutants is also comparatively large. For example, emission factors for particulate emissions from oil fires of between 4 and about 17% of the fuel mass were found in the literature.

Nevertheless, the figures summarised in Table 3.3 remain – at the time of preparing this report - our best estimates of the total quantities of air pollutants emitted during the Buncefield incident.

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[1] Please see http://www.buncefieldinvestigation.gov.uk/index.htm

Figure 3.1 Inside the depot during the fires © the Hertfordshire Fire and Rescue Service

Figure 3.2 Devastated tanks after the fires © the Hertfordshire Fire and Rescue Service

4 Air Quality Monitoring

Hourly automatic air quality monitoring in the UK's national Automatic Urban and Rural Network (AURN) continued as usual and without interruption during the period of the incident. Pollutants measured include: particulate matter (both PM_{10} & $PM_{2.5}$), nitrogen dioxide (NO_2), sulphur dioxide (SO_2), carbon monoxide (CO) and ozone (O_3) Results were disseminated in near real-time through the UK Air Quality Archive at www.airquality.co.uk.

Regional air quality monitoring networks near Hemel Hempstead and in south-east England also continued to monitor during the incident; King's College Environmental Research Group (ERG) increased the frequency of updates on these networks to hourly during the course of the incident (www.londonair.org.uk). See Appendix H.

Targeted local monitoring was also carried out within the oil depot and the surrounding area by i) Netcen on behalf of Defra, and ii) the Fire Brigade's Scientific Advisors (Bureau Veritas) and the Health and Safety Laboratories (HSL) on behalf of Health Protection Agency- see Appendix H. Moreover, the Met office/NERC FAAM aircraft made extensive measurements from within the plume on 13th December 2005.

Figure 4.1 shows the locations of fixed automatic network monitoring stations in southeast England that were operational during the incident.

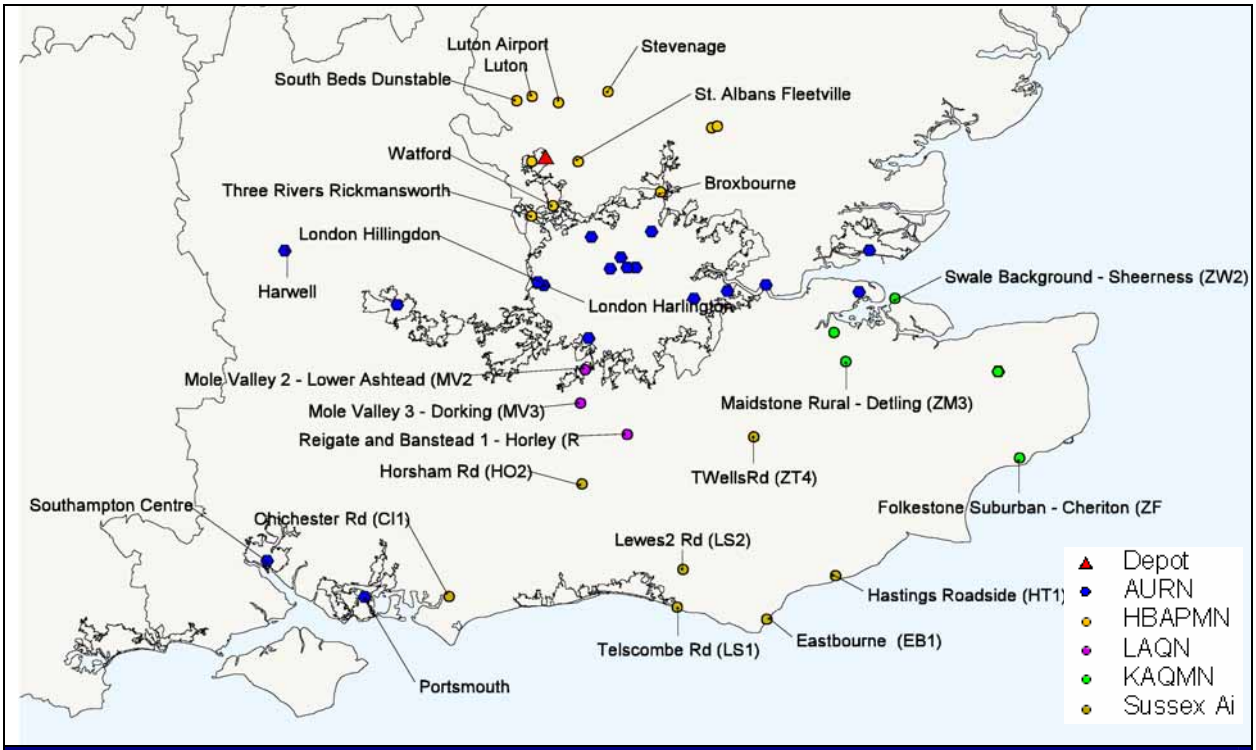

Figure 4.1 Location of air quality monitoring in southern England
(notes- Includes PM_{10} monitoring stations across SE; London Network not fully represented; does not include PAH measurement sites

4.1 MONITORING NETWORKS

Across southeast England, the AURN, as well as other local networks, operate continuously to provide near real-time air quality data and information to the public and authorities. Monitoring of air pollutants across England, Greater London and - in particular - near Hemel Hempstead continued uninterrupted during the fires. The different networks across England provided up-to-

date hourly measurements to the public through their respective websites, as noted above. AURN measurements were also made available to the media, as well as through TV Teletext services and a freephone telephone service at 0800 55 66 77.

Please note that all analyses reported here are based on provisional monitoring results (i.e. data have still to be verified through the comprehensive Quality Assurance and Quality Control -QA/QC- and ratification processes applied in UK national networks). Nevertheless, these measurements provide our most reliable indicator of potential public exposure to the plume from the fires.

4.1.1 Automatic Urban and Rural Network (AURN)

4.1.1.1 Air Quality Index

The UK Air Quality Index (AQI) is used to report hourly air quality concentrations. This index provides a simple measure of how clean or polluted the air is, together with an indication of possible health impacts. Appendix C illustrates how the AQI is calculated, as well as showing the possible health effects associated with each band: Low, Moderate, High and Very High.

AURN measurements did not show any instance during the Buncefield incident with PM_{10} levels of Moderate or above that were attributable to the fire. Table 4.1 summarises the stations across England that measured an AQI of moderate or above between 9th and 16th December 2005. Of the sites featuring in this table, Bradford Centre site was affected throughout this period by localised construction work; Camden Kerbside and London Marylebone are located close to major roads (less than 1 metre from the kerb) and are therefore substantially affected by local transport sources. Haringey Roadside measured Moderate levels due to PM_{10}, but this was before the event.

None of the AQI moderate, high or very high events featuring in Table 4.1 therefore appear related to the Buncefield incident. All other AURN stations recorded low levels of pollution throughout.

Table 4.1 Stations measuring AQI Moderate or above between 9th and 16th December 2005

Station	Date	Max hourly mean (μgm^{-3})	Air Quality Index
Bradford Centre	09/12/05	66	Moderate
Bradford Centre	10/12/05	63	Moderate
Bradford Centre	12/12/05	57	Moderate
Bradford Centre	13/12/05	97	High
Bradford Centre	14/12/05	97	High
Bradford Centre	15/12/05	130	Very High
Bradford Centre	16/12/05	129	Very High
Camden Kerbside	12/12/05	54	Moderate
Camden Kerbside	13/12/05	60	Moderate
Camden Kerbside	14/12/05	59	Moderate
Camden Kerbside	15/12/05	50	Moderate
Haringey Roadside	10/12/05	52	Moderate
London Marylebone Road	09/12/05	55	Moderate
London Marylebone Road	10/12/05	67	Moderate
London Marylebone Road	11/12/05	62	Moderate
London Marylebone Road	12/12/05	51	Moderate

Figure 4.2 shows the 24-hour running mean PM_{10} measurements for all stations in England[6] between 9th and 16th December 2005. Apart from the roadside stations shown in Table 4.1, all other stations recorded low levels of air pollution. This figure presents monitored concentrations across different sites and against the 24-hr running mean air quality statistic on which UK Air Quality Indices are based (dotted red line).

[6] Figure 4.2 excludes data from the Bradford Centre station as it would obscure the rest of the data.

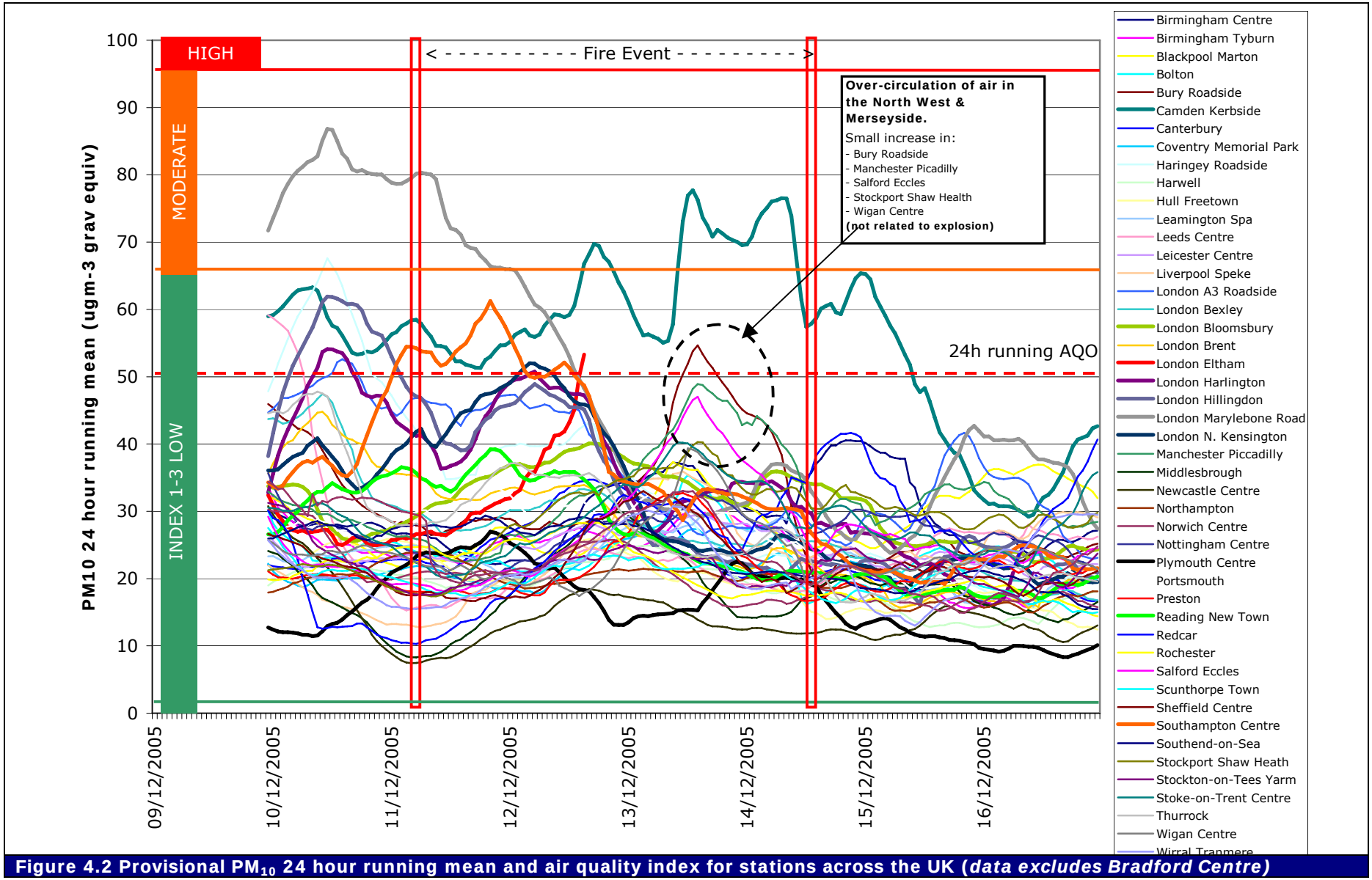

Figure 4.2 Provisional PM_{10} 24 hour running mean and air quality index for stations across the UK (*data excludes Bradford Centre*)

4.1.1.2 Air Quality Data

Particulate Matter (PM_{10}) concentrations measured in the AURN have been used as an indicator to assess ground-level air quality impacts of the Buncefield fire. Levels of nitrogen dioxide (NO_2), sulphur dioxide (SO_2), carbon monoxide (CO) and ozone (O_3) were not apparently affected by the fire and remained low during the event.

Particulate Matter PM_{10} data are monitored in the AURN using the TEOM (Tapered Element Oscillating Microbalance) instrument that provides 15-minute mean measurements[1]. As shown in Figure 4.1, there were a number of fixed monitoring stations measuring PM_{10} near the depot, as well as downwind of the fire.

With the exceptions described in the previous section, PM_{10} levels across the UK were classed as Low between 9th and 16th December 2005. Fifteen-minute mean and hourly concentrations will clearly provide a better way of identifying short-lived incidents of plume grounding than 24-hourly means. However, 24-hourly running means offer a better indication of potential public health impacts.

Figure 4.3 shows the 15-minute mean PM_{10} concentrations at a number of locations across England. Levels at the Bradford Centre site clearly stand out. However, these were directly linked to stone cutting arising from local construction work and are clearly not attributable to the Buncefield fire; in fact, these transient peaks had been occurring for several months before, during and after the Buncefield event. Other elevated concentrations were measured at Camden Kerbside and Marylebone Road; these were both due to traffic related emissions. Figure 4.4 shows the same data without Bradford Centre and using an expanded scale to show greater detail.

Please note that annual PM_{10} time series graphs for these and a number of AURN monitoring stations are provided in Section 4.2 These figures provide useful information on Buncefield period measurements when examined within a broader annual context.

With the exception of the monitoring stations discussed above, the majority of the 15-minute PM_{10} concentrations recorded in the AURN during the event were well below 100 μgm^{-3}. The highest 15-minute PM_{10} value measured was 133 μgm^{-3} at Southampton Centre on 11th December at 8:15 pm. Hourly PM_{10} concentrations illustrated in Figure 4.5 show that none of the sites recorded levels exceeding 150 μgm^{-3}, whilst the majority of the hourly averages remained well below 100 μgm^{-3}.

Hourly PM_{10}/NO_2 concentration ratios for some AURN monitoring sites have been calculated and graphed. These ratios are used to identify whether a peak is due to an unusual event or just an increase in pollution from a local source. For a roadside site, it would be expected that any increase in PM_{10} concentrations would be proportional to any corresponding increase in NO_2 concentrations; this is because both pollutants have a common source- traffic. If the PM_{10}/NO_2 ratio increases substantially, however, it may be concluded that the PM_{10} source is different from the NO_2 source.

PM_{10}/NO_2 ratios have therefore been used to try to identify the likely origin of the PM_{10} peaks measured during the incident. Appendix B examines ratios for several AURN stations, including Southampton Centre and Marylebone Road. None of the ratios appear to have changed during the time period; this suggests that these relatively small peaks were not linked to the Buncefield event.

Additional NAME modelling analyses have been carried out by the Met Office to determine the origin of the air contributing to Southampton Centre's 15-minute PM_{10} peak. These analyses, included in full in Appendix E, show that the 15-minute peak in PM_{10} concentrations measured at this location was not due to the fire at Buncefield.

In conclusion, there was no evidence of plume grounding from AURN air quality measurements. Pollutant levels were all within normal ranges. Moreover, air origin maps from NAME modelling did not support the view that small localised peaks in AURN PM_{10} levels had originated from the Buncefield oil depot.

In Section 4.1.2, we examine corresponding data from non-AURN monitoring stations operational in Southern England at the time.

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[1] The TEOM instrument is widely used in UK and worldwide. It is based on the real-time measurement of oscillations in a tapered element microbalance; as the element becomes progressively loaded with deposited particles, its resonant frequency changes. Measuring this provides a reliable indication of ambient particle concentrations.

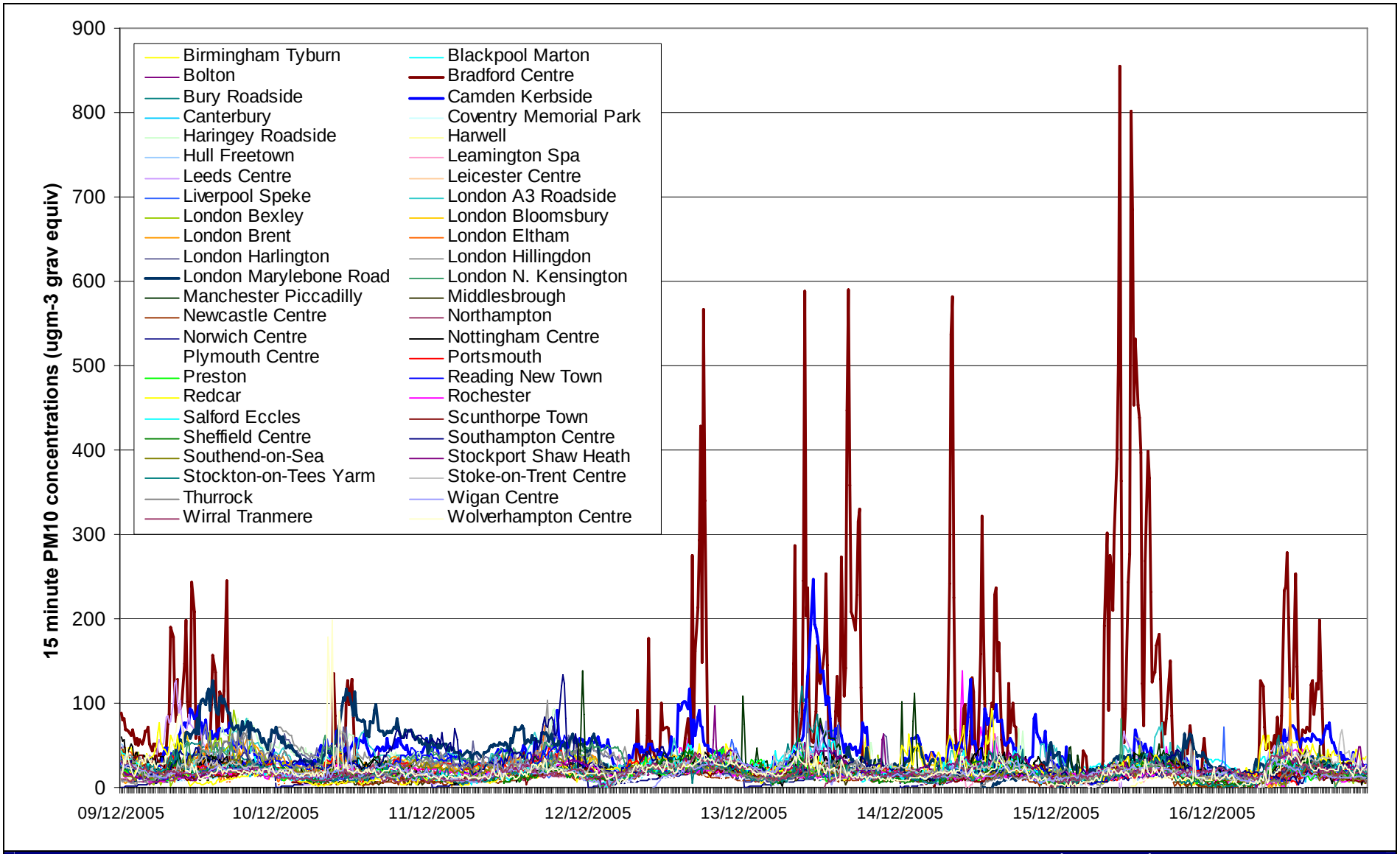

Figure 4.3 Provisional 15-minute PM_{10} measurements across AURN stations in England between 9th and 16th December 2005

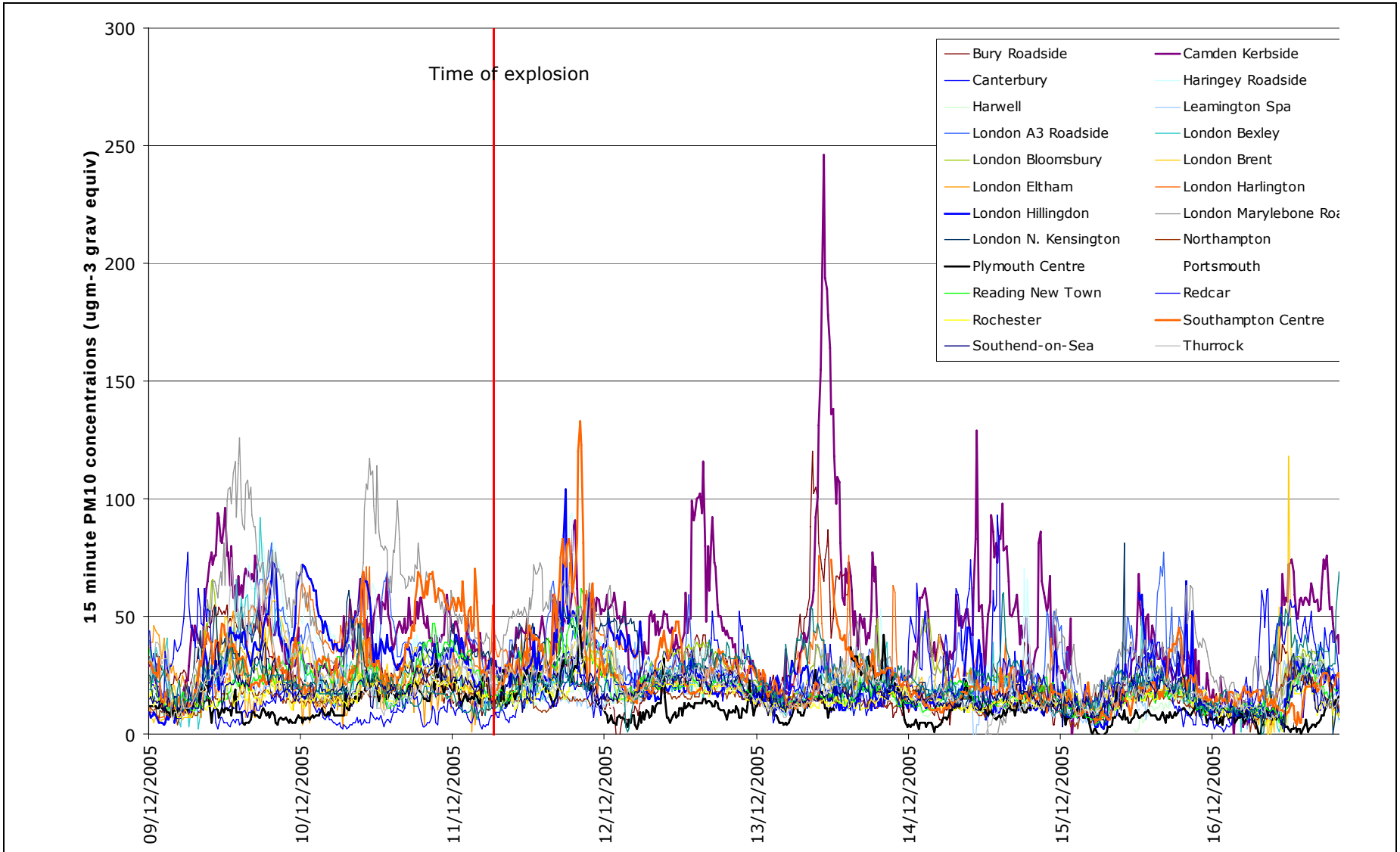

Figure 4.4 15-minute mean PM_{10} measurements between 9th and 16th December 2005 at selected sites across the AURN in England

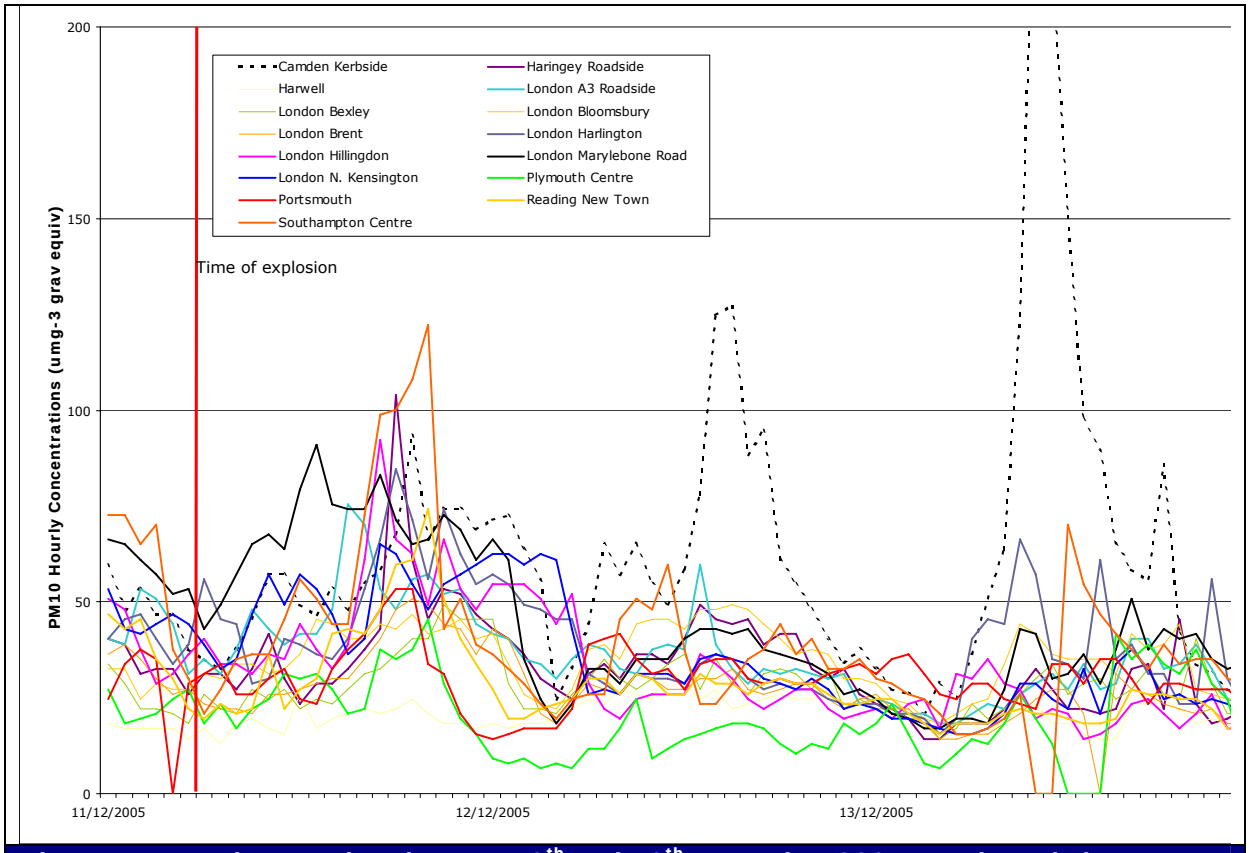

Figure 4.5 Hourly PM_{10} data between 9th and 16th December 2005 at selected sites across the AURN in England

4.1.2 Local Networks

In addition to data from the AURN, measurements from local air monitoring networks have been analysed in this report. These include:

- Herts & Beds Air Pollution Monitoring Network (HBAPMN) www.hertsbedsair.org.uk
- London Air Quality Network (LAQN) www.londonair.org.uk
- Kent Air Quality Monitoring Network (KAQMN) www.kentair.org.uk
- Sussex Air www.sussex-air.net

4.1.2.1 HBAPMN

As can be seen in Figure 4.1, the HBAPM Network surrounds Buncefield oil depot. Figure 4.6 shows the 15-minute mean PM_{10} concentrations at six background stations in this local network. The highest two values measured were 133 μgm^{-3} at 8:30 pm on 11th December at St Albans Fleetville and 98 μgm^{-3} at 5:30 am on 12th December at Three Rivers Rickmansworth station. These levels are not particularly high and are, in fact, similar to those measured before the event (Section 4.2). They are also typical of measurements at AURN stations during the period. Please note there is a decrease in background levels after the 12th, due to changes in weather conditions and air mass origins (Section 5).

4.1.2.2 LAQN, KAQMN and Sussex Air

PM_{10} levels were also measured at monitoring stations in the LAQN, KAQMN and Sussex Air networks. Figure 4.7 shows the 15-minute mean PM_{10} concentration measurements at all stations measuring PM_{10} across these networks (excluding most of London's sites). The highest peaks were measured on 11th December. Horsham Roadside measured a 15-minute mean PM_{10} concentration of 290 μgm^{-3} at 10:45 pm, Lewes 2 Roadside recorded a peak 15-minute mean PM_{10} concentration of 217 μgm^{-3} at 7:15 pm; the corresponding maximum 15-minute mean PM_{10} concentration at Mole Valley Urban Background site was 156 μgm^{-3} at 4:15 pm.

It should be emphasised that these levels are the **highest** measured across these networks during the incident. Nevertheless, as shown in Figure 4.8, they were not particularly high in absolute terms, resulting in an Air Quality Index of Moderate for a very short time only. In fact, pollution levels were within normal ranges for the time of year and prevailing meteorology (see Section 4.2).

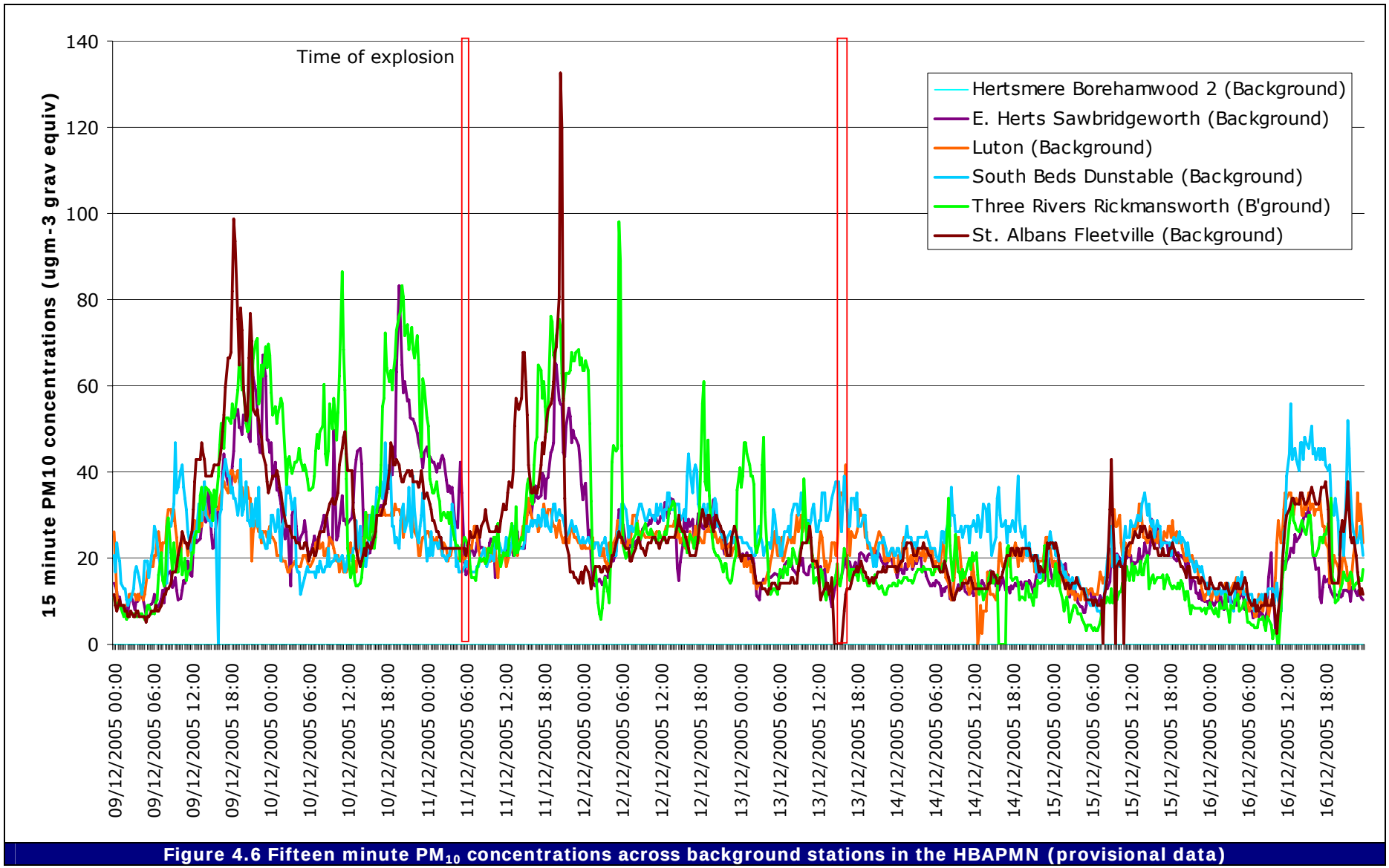

Figure 4.6 Fifteen minute PM_{10} concentrations across background stations in the HBAPMN (provisional data)

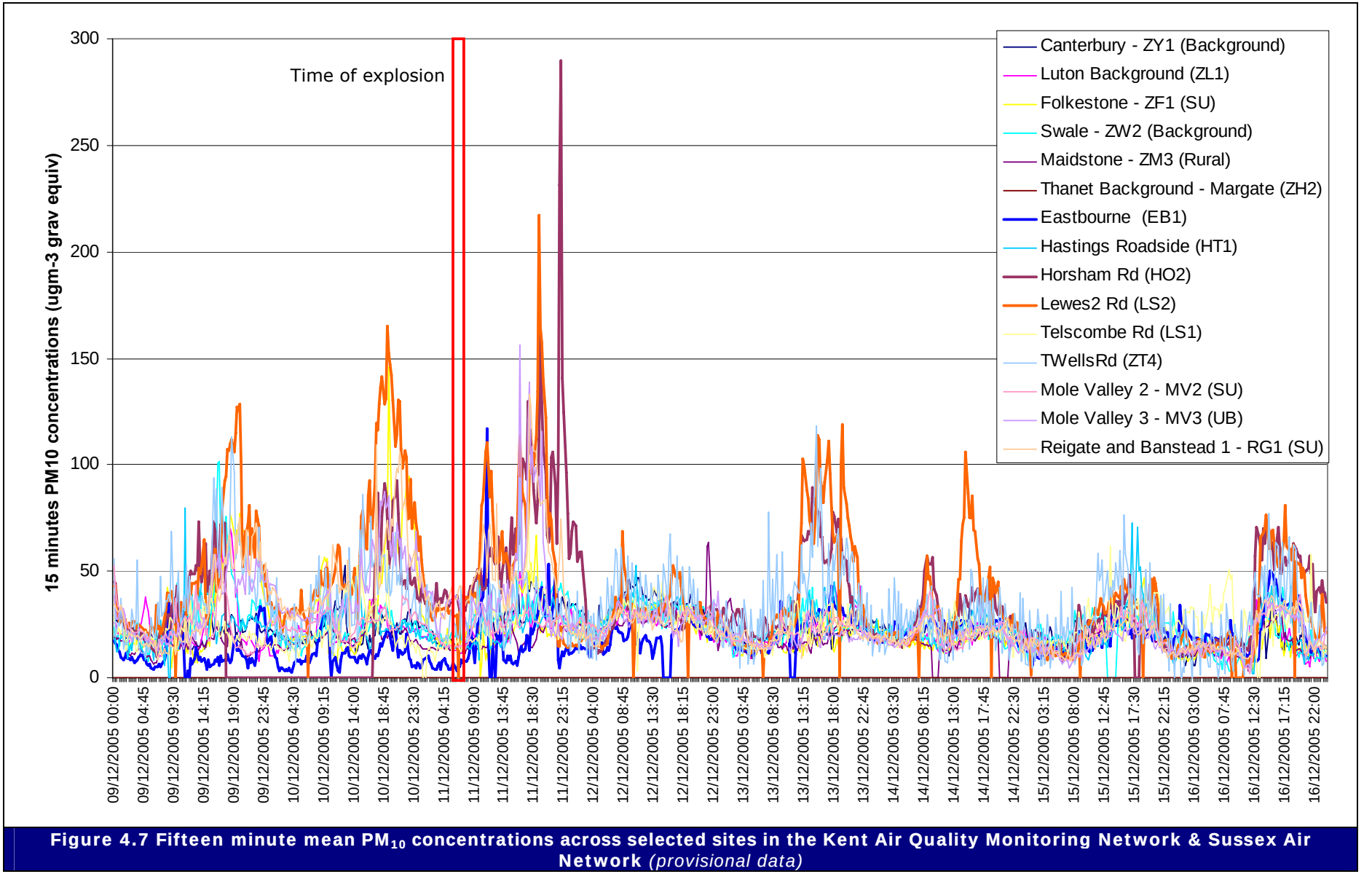

Figure 4.7 Fifteen minute mean PM_{10} concentrations across selected sites in the Kent Air Quality Monitoring Network & Sussex Air Network *(provisional data)*

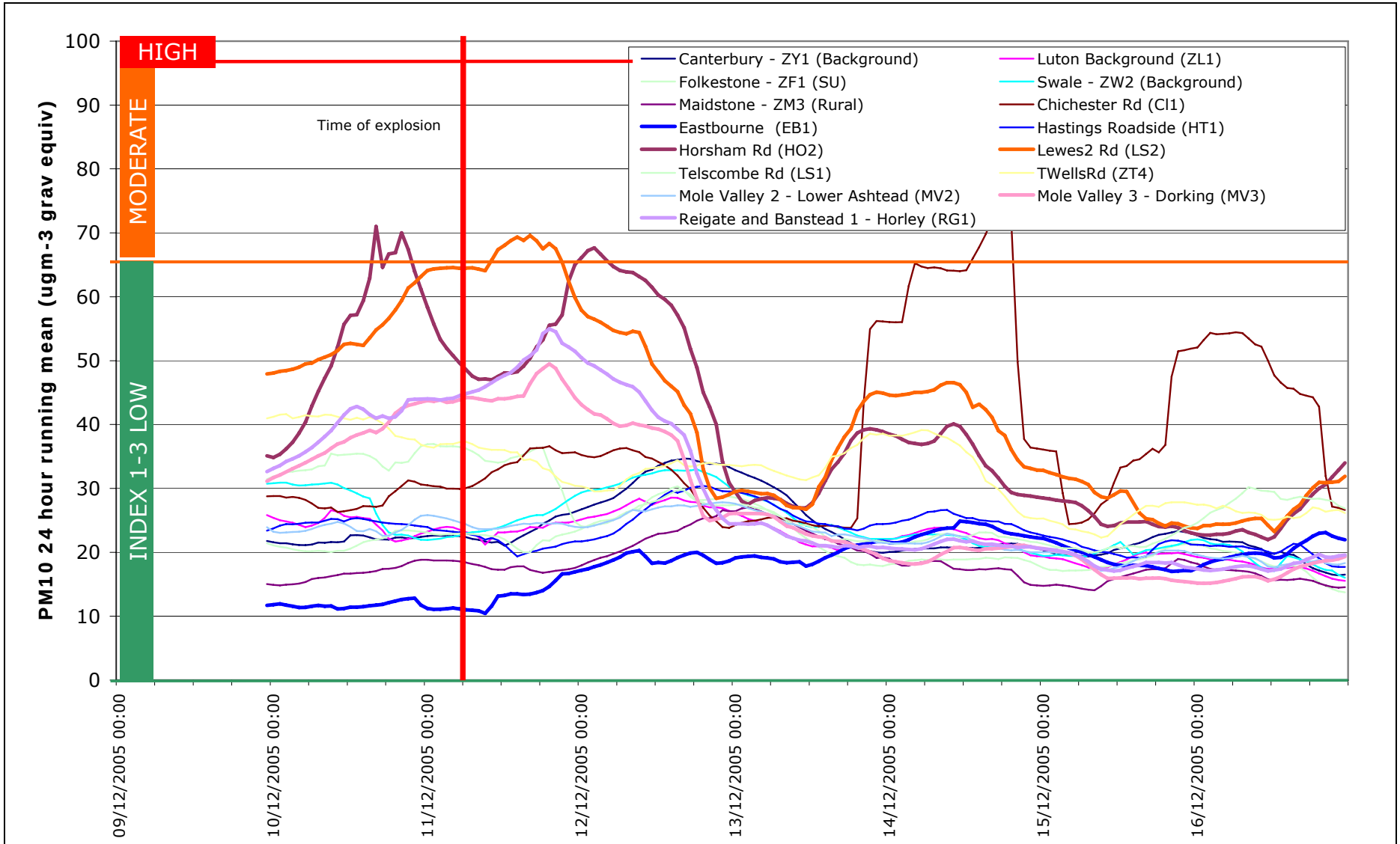

Figure 4.8 PM_{10} 24-hour running mean and air quality index for selected stations LAQN, KAQMN and Sussex Air

Examining the measured PM_{10}/NO_2 ratios at the Horsham Roadside site (see Figure 4.9), it appears that the peak in PM_{10} concentrations on the 11th is not directly related to the traffic emissions and may therefore be of a different origin. Assuming that the data are not faulty, it would appear that the elevated peak is related to another source. This could, of course, include grounding of the plume from the Buncefield fires. This may also be the case for Lewes Roadside (Figure 4.10), but the evidence here is less clear.

NAME back map analyses carried out by the Met Office to determine the origin of the air contributing to Horsham's 15-minute PM_{10} peak are included in Appendix E. These demonstrate that the Buncefield oil depot plume could have contributed to the peak in PM_{10} concentrations at Horsham Roadside.

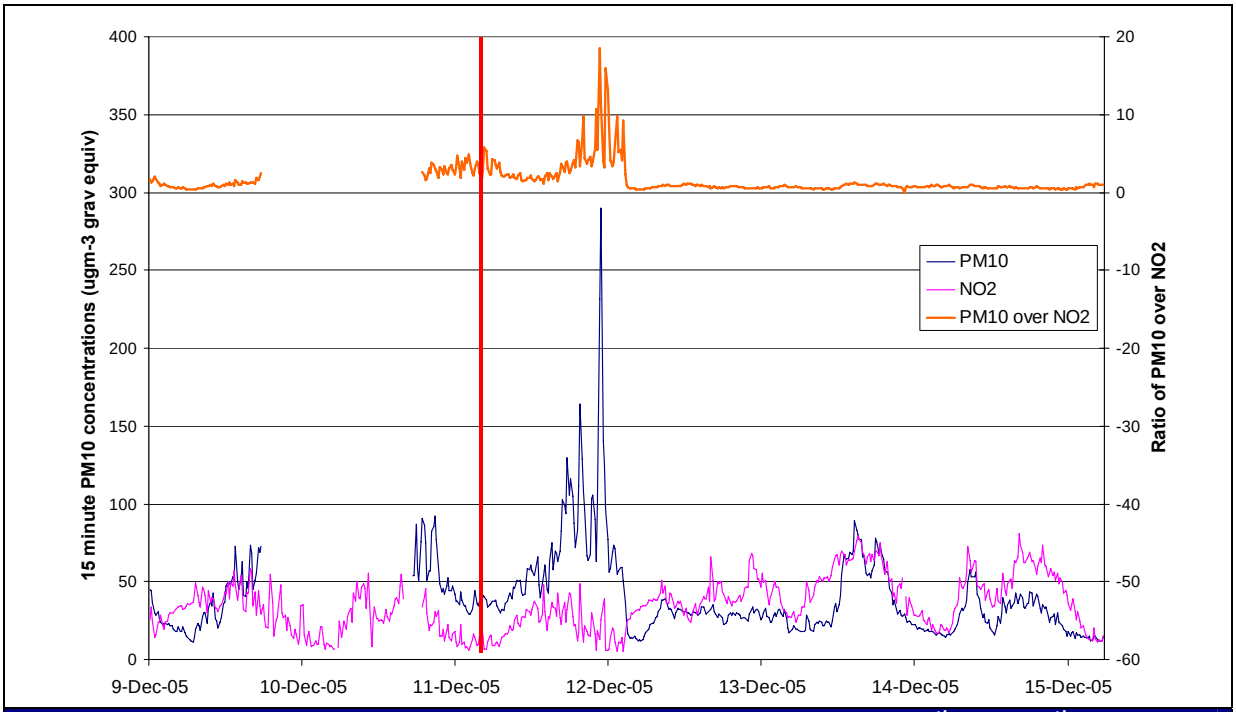

Figure 4.9 Horsham Roadside PM_{10} and NO_2 relationship between 9th and 15th Dec 2005

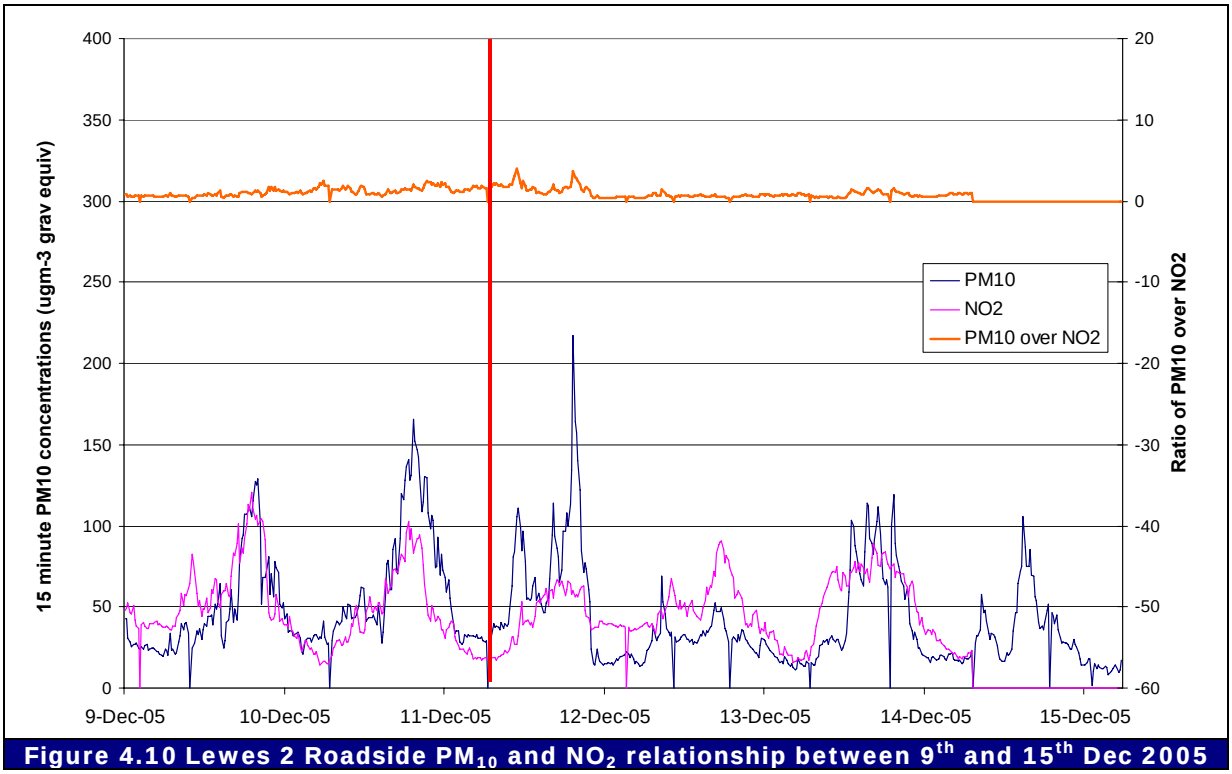

Figure 4.10 Lewes 2 Roadside PM_{10} and NO_2 relationship between 9th and 15th Dec 2005

4.1.3 Monitoring Networks in France

There are several local monitoring networks across northern France continuously measuring air pollution. Provisional data from these networks have been used to assess if the Buncefield fire had any trans-boundary impact. In particular, data from the following four networks have been reviewed (Figure 4.11):

- Air Pays de la Loire
- Air Normand
- Air C.O.M.
- Airbreizh

Figure 4.11 Air quality networks across northern France
(http://www.air-lr.asso.fr/reseau_nat.asp)

Hourly mean PM_{10} concentrations between 9th and 16th December 2005 for stations from the four networks across north-west France are summarised in Appendix E. The highest hourly values were measured at Caen and Cherbourg before the event. After 11th December, the highest values were measured at Le Havre, Caen and Cherbourg. However, these levels are below 100 μgm^{-3} and the UK AQI remained Low across the networks.

NAME modelling analyses were carried out by the Met Office to determine the origin of the air contributing to the peaks on 11th December at Le Havre and Cherbourg; these are included in Appendix E. These analyses show that the Buncefield plume did not contribute to the measured PM_{10} peaks at these locations.

During the Buncefield event, there was no evidence from the monitoring networks of pollution in northern France that had been transported from the Buncefield fires.

4.1.4 PAH network

Apart from the AURN and other local networks measuring the most common pollutants such as PM_{10}, there are other continuously operating networks in the UK, including the PAH (Polyaromatic hydrocarbons) and Hydrocarbon Networks. Results from these are presented below.

The polycyclic aromatic hydrocarbon (PAH) monitoring network provides measurements of PAH concentrations at 24 sites across the UK. PAHs are a group of chemicals consisting solely of carbon and hydrogen that are emitted during combustion processes, particularly when these are incomplete. Routine samples are taken over 14-day periods and are combined to provide quarterly average concentrations for 34 individual PAHs. The air quality objective for PAHs is expressed in terms of an annual average of a representative compound- benzo[a]pyrene. Three of the network

sites are in the southeast of England; at Brent (Kingsbury High School), London (Victoria Street) and Bromley (Crystal Palace Parade).

Data from the PAH Network were made available shortly after the fire. Initial analyses of these data are presented in a letter report from Peter Coleman (Netcen) to Martin Meadows (Defra), included in Appendix F. This report found that, during the week in which the Buncefield oil depot was burning, the concentrations of dioxins and PAHs rose at the three Greater London sites (Brent, London Victoria Street and Bromley).

The report noted, however, that this increase in concentrations during the fire did not follow that expected geographically from the proximity of the individual sites to the fire – levels at Brent increased most, whilst levels at Bromley increased more than those at Victoria Street. The increase in individual compounds was not consistent between sites, moreover. The report concluded that further dispersion modelling, together with analysis of additional samples from the PAH network, would be required to confirm whether the recorded increase in PAH and dioxin concentrations resulted from plume grounding in London or could merely reflect normal temporal variability in concentrations of these pollutants.

Additional analyses were then carried out on earlier and later samples from the three London sites. (Appendix G). In view of the short-term peaks in PM_{10} discussed below at Horsham and Lewes, the contemporary samples from the Hove site were also analysed for PAHs.

These later analyses also indicate that PAH measurements were not influenced by the Buncefield incident. Measurements of PM_{10} and nitrogen dioxide at London Brent do not follow the trend in Benzo[a]pyrene concentrations, and show no significant signal during the period of the incident. Increased individual PAH and dioxin concentrations were seldom observed; those that did occur, did not appear to be related to the proximity of the measurement site to the incident.

The analysis of filters taken by the aircraft show low concentrations of PAHs and dioxins, below those measured at the sampling sites. Hence, while the smoke from the Buncefield fire may have increased concentrations of PAHs and dioxins at the four South East England PAH network sites, this increase was no greater than the ongoing variability in PAH concentrations. Overall, a PAH 'signal' due to the fire cannot be demonstrated, therefore.

4.1.5 Hydrocarbon Networks

The UK Ambient Automatic Hydrocarbon Air Quality Network consists of five monitoring stations, each measuring between six and twenty-nine hydrocarbon compounds. Three of the sites - Glasgow, Cardiff and Harwell - use Environnement VOC71M analysers to report 1,3 butadiene and the BTEX aromatic compounds. The remaining two sites - Eltham and Marylebone Road - both in London, use Perkin Elmer ozone pre-cursor analysers to report the full range of hydrocarbon species on the European Union's 4th Daughter Directive list[1].

Marylebone Road in London is the closest site in the Hydrocarbon Network to Hemel Hempstead. Figure 4.12 shows hourly concentrations of some selected hydrocarbons at Marylebone Road. These levels are within the normal range for this site.

Figure 4.13 shows the ratio of all measured aromatic compounds to benzene. These ratios are used to identify any unusual event in the data. The graph may help to highlight a different source of pollution to those usually affecting the site and could therefore indicate Buncefield plume grounding. The ratios to benzene are fairly stable, but the measurement at 3:00 pm on 11th December stands out. This sample shows elevated toluene, xylenes and trimethylbenzenes. Benzene, all other VOCs, PM and inorganic data did not rise during this hour, however.

This is the only unusual measurement noted in the Hydrocarbon Network during the event. The elevated compounds are the same as those also observed in grab samples taken near the depot (see Section 4.3.2); this may indicate a relationship. However, there are a number of alternative and more local sources of such short-term changes in the VOC profile, such as fuel evaporation or paint fumes.

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[1] Directive 2004/107/EC of the European Parliament and of the Council of 15 December 2004 relates to arsenic, cadmium, mercury, nickel and polycyclic aromatic hydrocarbons in ambient air. More detailed information, in particular in relation to PAHs and benzo[a]pyrene may be found at: http://europa.eu.int/eur-lex/lex/LexUriServ/LexUriServ.do?uri=CELEX:32004L0107:EN:HTML

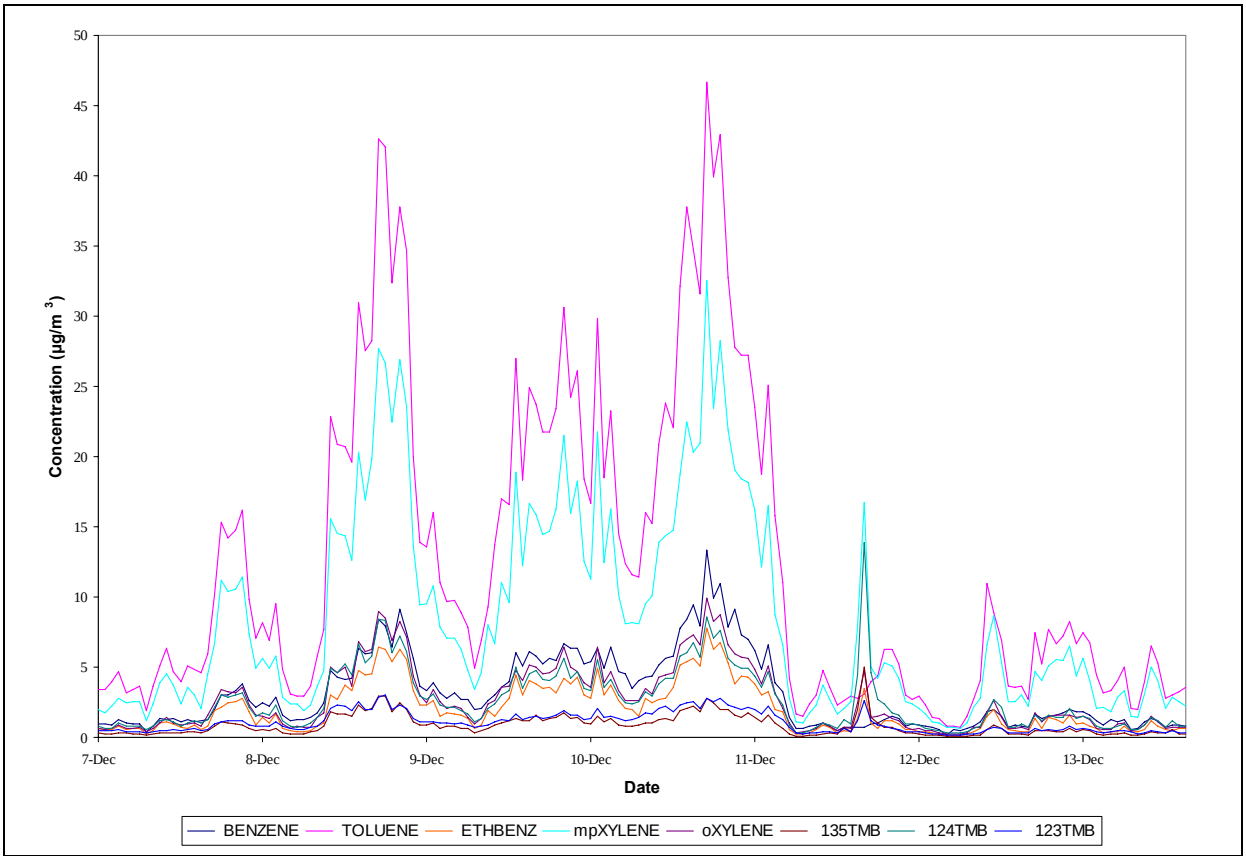


Figure 4.12 Hourly concentrations of selected hydrocarbons at London Marylebone Road

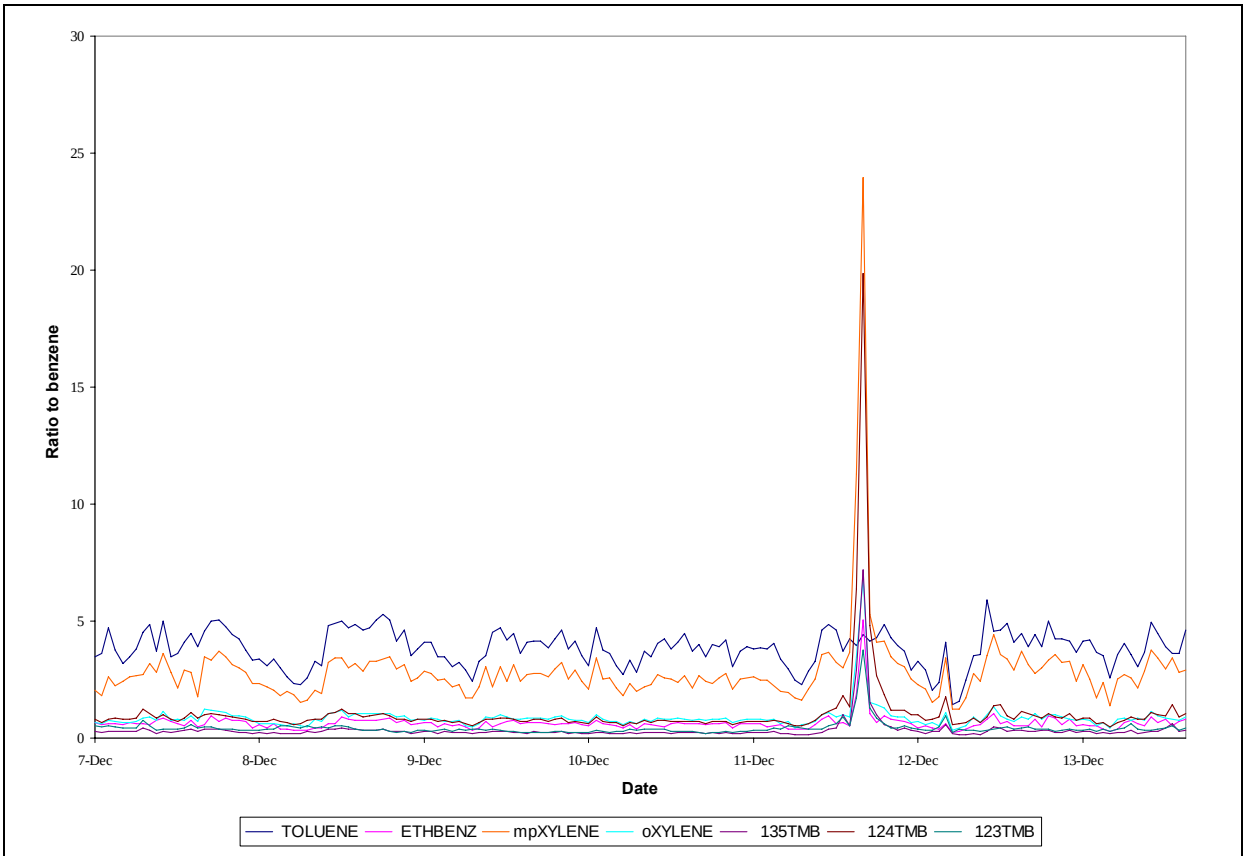


Figure 4.13 Ratios of all aromatic compounds to benzene at London Marylebone Road

4.2 AIR QUALITY MEASUREMENTS DURING BUNCEFIELD SET IN A BROADER TIMEFRAME

4.2.1 Annual time series comparison

As noted in the previous sections of this report, monitoring undertaken in a number of UK networks during the week following the Buncefield oil depot explosion did not highlight – with the exception of the Horsham, Lewes Roadside Marylebone Road measurements discussed previously - any significantly elevated air pollution concentrations. In this section, we illustrate and re-enforce this observation by examining the measurements in the broader context of the year as a whole.

The data presented in Figures 4.14a and b are from a range of networks. We have, in particular, selected monitoring sites discussed in previous sections; this makes the graph easier to interpret than were we to graph all datasets. Data from sites in the UK Automatic Urban and Rural Network (AURN) for 2005 have been fully ratified by Netcen. Where data capture statistics were below 75%, sites were omitted from the analysis. Also presented are monitoring data from locations in close proximity to the Buncefield oil depot. These sites were part of the Sussex Air Quality Steering Group Network (http://www.sussex-air.net/) and the Hertfordshire & Bedfordshire Air Pollution Monitoring Network (http://www.hertsbedsair.org.uk/hertsbeds/asp/home.asp).

Figure 4.14a shows the daily average PM_{10} concentrations at selected sites throughout 2005. It confirms the unexceptional magnitude of the measurements recorded during the Buncefield week. The only data that stand out from this analysis are those for Bradford Centre. As already discussed, however, these are directly attributable to local construction work, including stone cutting, in the immediate vicinity of the monitoring hut. PM_{10} peaks are, in fact, seen at this site before and after the Buncefield event, and continue to this time.

Please note that, in order to filter some of the day-to-day statistical 'noise' from these graphs, we repeat the analysis in Figure 4.14b, but this time using 1-week (168-hour) running averages.

4.2.2 A comparison with Bonfire Night

Figure 4.15 compares PM_{10} concentrations measured throughout the AURN during the Buncefield incident with those recorded during a range of recent Bonfire Night weeks. Bonfire Night particle concentrations depend critically on weather conditions and timing, and therefore vary markedly from year to year, The graphed Bonfire night events (1995, 2001, 2005) have been selected as being typical of high, medium and low-intensity events of this type, respectively.

Please note that the running 24-hour average metric plotted here conforms to the Defra Health bandings for PM_{10}. Note, also, that the data graphed are network averages over the whole of the AURN (for sites with >75% data capture).

Although the different time series in Figure 4.15 are not strictly comparable, because they do not cover the same time periods or the same geographical scale (Bonfire Night being nationwide and Buncefield more localised), they nevertheless serve broadly to demonstrate the magnitude of the Buncefield event when compared against recent Bonfire Nights. It is clear that the Buncefield event was associated with PM_{10} concentrations similar to those observed during Bonfire Night 2005. However, as the result of favourable meteorological factors, the 2005 event did not exhibit any significant increase in particle levels above background.

Figure 4.14a Daily average time series PM_{10} concentrations (TEOM, μgm-3), 2005

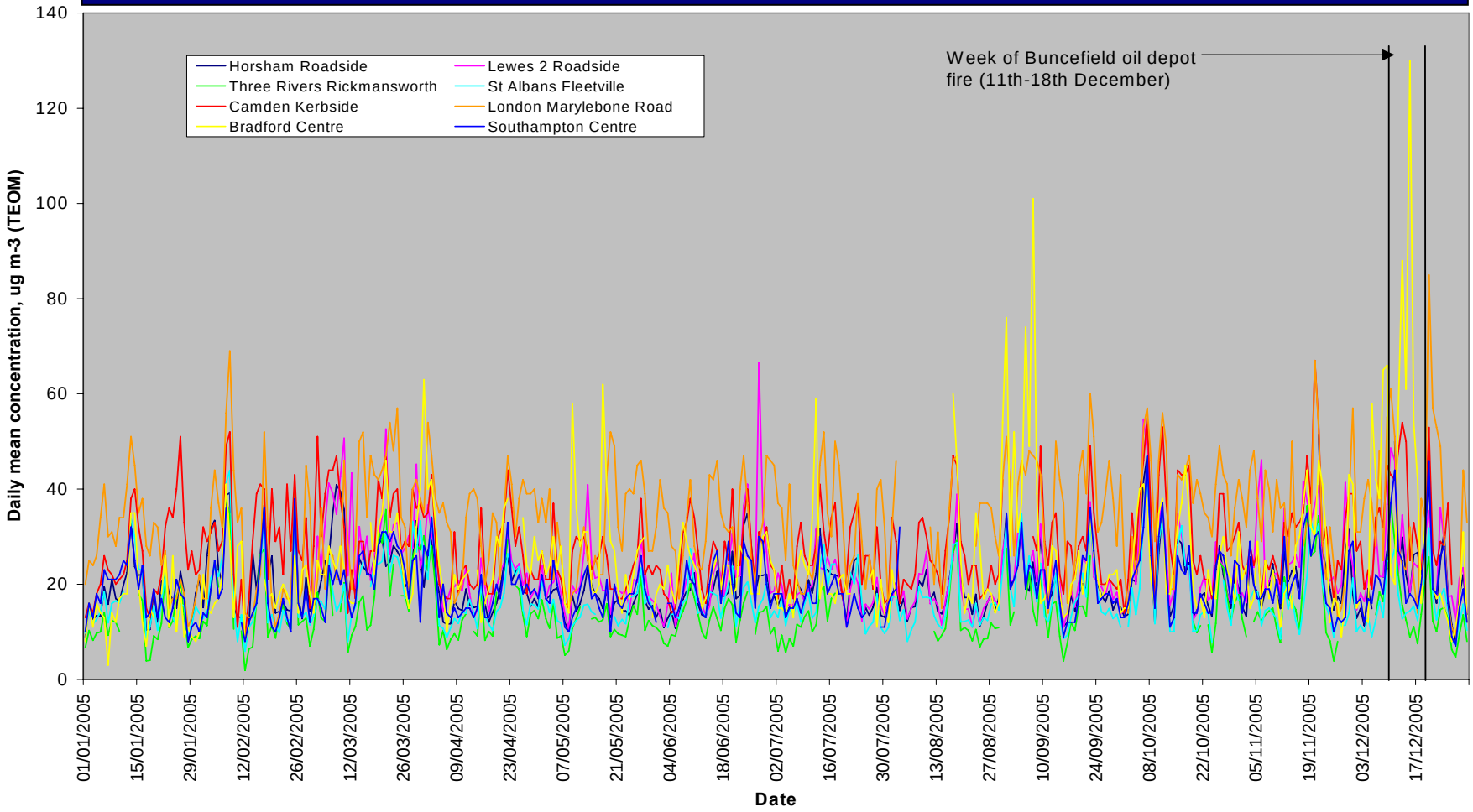


Figure 4.14b Running 168-hour average time series PM_{10} concentrations (TEOM, μgm-3), 2005

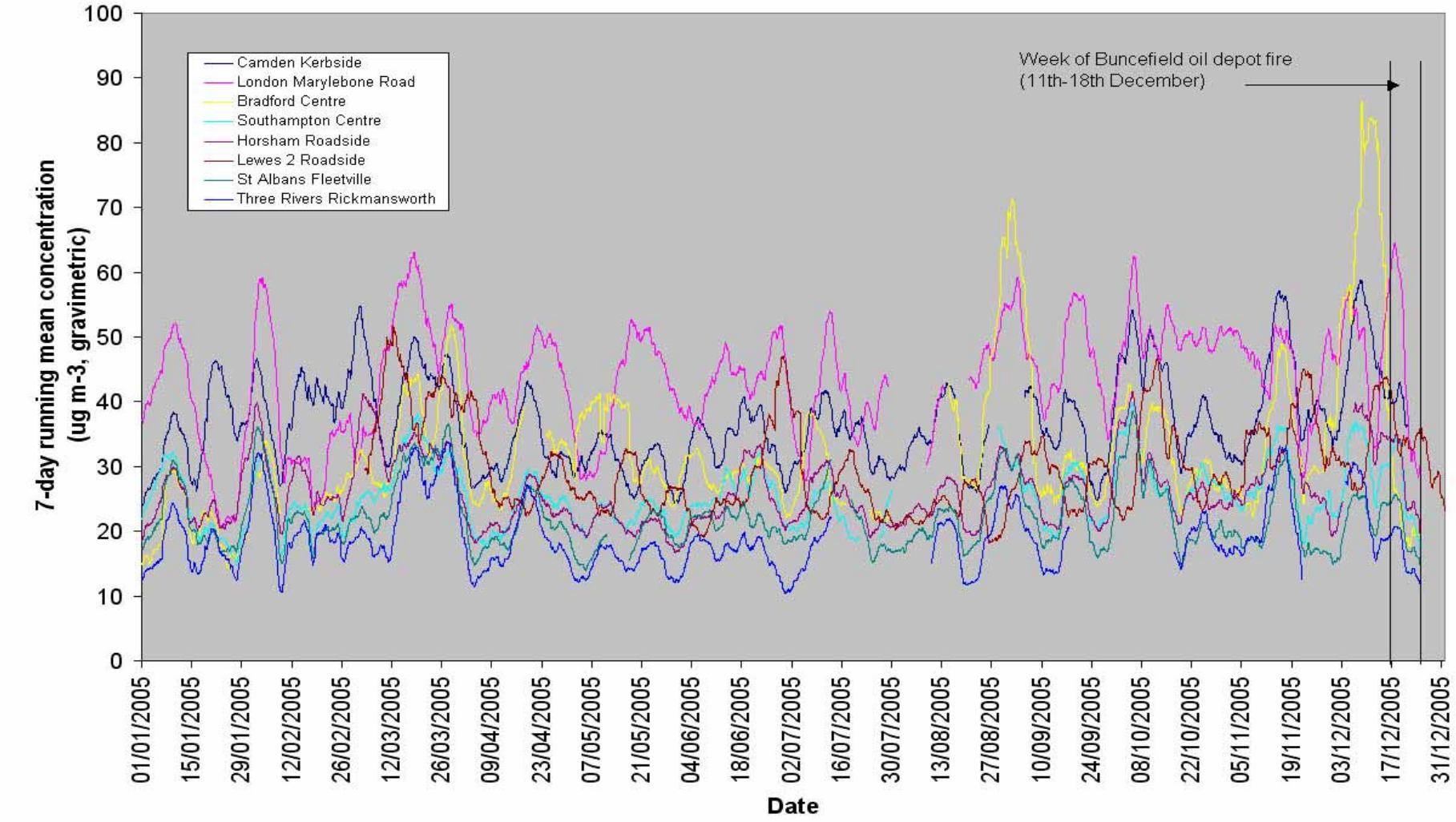
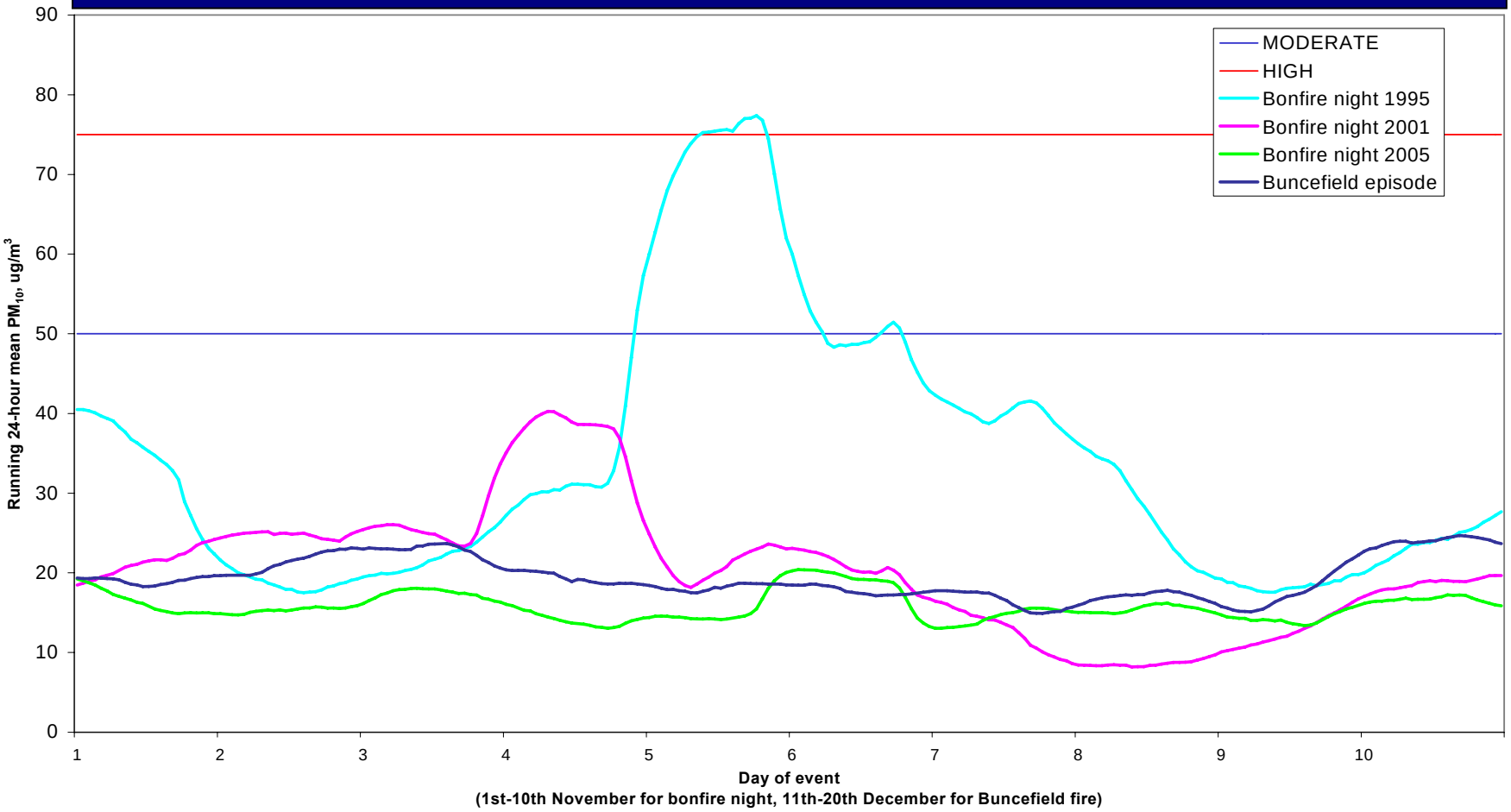


Figure 4.15 Running 24-hr average PM_{10} concentrations (μgm^{-3}, TEOM) in the Automatic Urban and Rural Monitoring Network during the Buncefield fire and during Bonfire Night



4.3 TARGETED LOCAL MONITORING

Apart from data from the well-established permanent monitoring networks presented in Section 4.1, targeted local monitoring was carried out around the oil depot and surrounding areas by i) Netcen on behalf of Defra and the DAs and ii) by the Fire Brigade's Scientific Advisors (Bureau Veritas) and HSL on behalf of the HPA (see Appendix H). The Met Office/NERC FAAM aircraft also made extensive measurements from within the plume on 13/12/05.

During the fire, Netcen carried out targeted monitoring of particulate matter and VOCs both inside and outside of the oil depot. Measurements between 12th and 14th December included:

- Particulate matter using a Grimm particulate sampler.
- Grab sampling for VOCs.
- Monitoring by the Fire Brigade's Scientific Advisors (Bureau Veritas) and HSL on behalf of the HPA for CO, CO_2, SO_2, particulate matter, hydrocarbons and VOCs

Figure 4.16 shows the exact locations of the Netcen targeted monitoring.

4.3.1 Particulate Matter in Buncefield

Using a Grimm particulate sampler, Netcen obtained particulate matter measurements from the oil depot site and surrounding areas. A portable dust analyser (GRIMM 1.101) was used to gauge concentrations of particulate matter. The GRIMM dust monitor is capable of simultaneously measuring in real time the Inhalable, Thoracic and Alveolic dust masses.

This monitoring targeted the areas of maximum visible impact of the plume, aiming to measure the likely highest concentrations at ground level. Figure 4.16 shows the location of the different sample points. Indicative measurements of PM_{10}, $PM_{2.5}$ and PM_1 are shown in Figures 4.17 to 4.20.

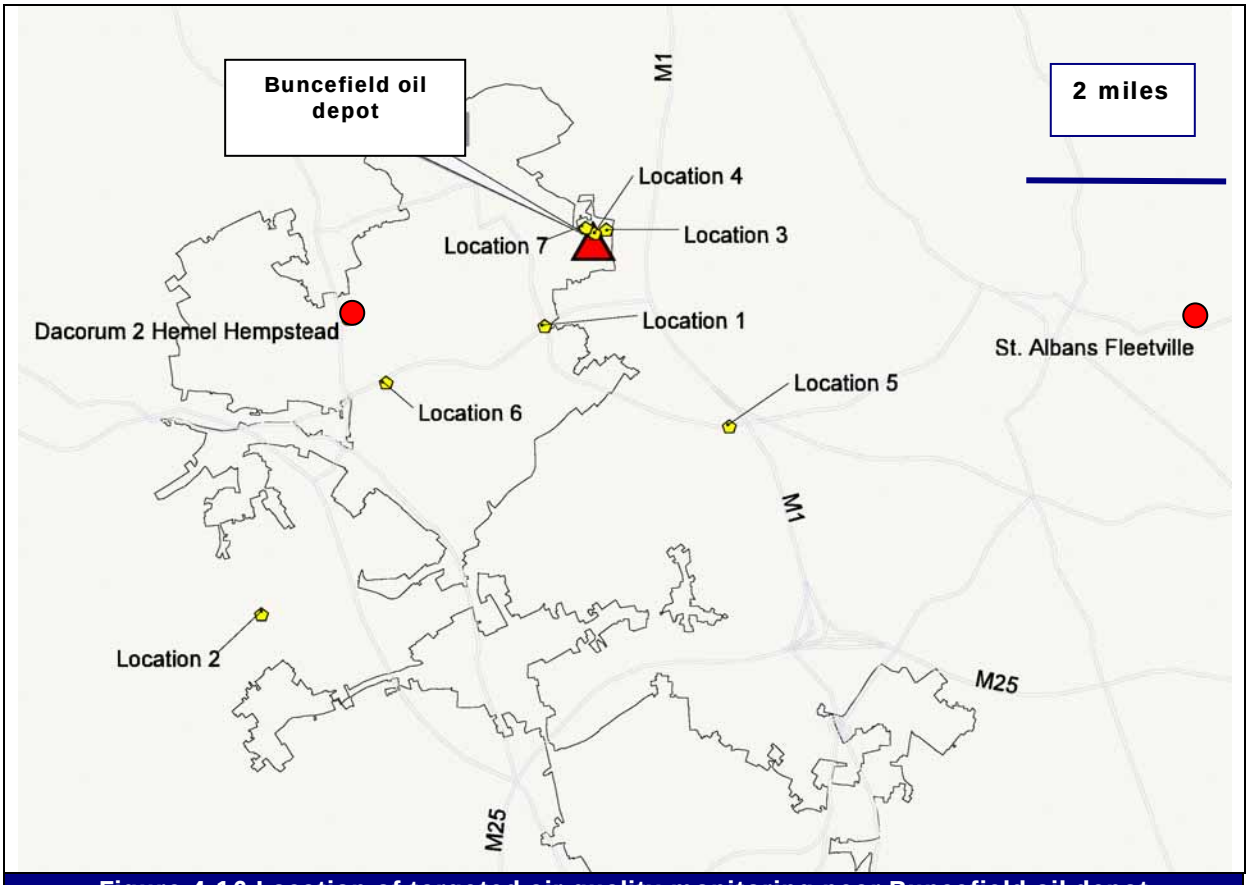


Figure 4.16 Location of targeted air quality monitoring near Buncefield oil depot

PM_{10}

One-minute averages were obtained, giving a high temporal resolution. The maximum indicative PM_{10} one-minute mean measurement was 985 μgm^{-3} on 12/12/05 at 6:08 pm at location 1. The

maximum 15-minute mean indicative measurement was 340 μgm^{-3} on 13/12/05 at 2:15 pm at location 4 (See Figure 4.20).

$PM_{2.5}$
The maximum indicative one-minute mean $PM_{2.5}$ measurement was 801 μgm^{-3} at location 4 on 13/12/05 at 2:18 pm. The corresponding peak 15-minute mean indicative measurement was 318 μgm^{-3} at location 4 on 13/12/05 at 2:30 pm (See Figure 4.20).

PM_1
The maximum indicative one-minute mean PM_1 measurement was 522 μgm^{-3} at location 4 on 13/12/05 at 2:21 pm. The maximum 15-minute mean indicative measurement was 210 μgm^{-3} at location 4 on 13/12/05 at 2:15 pm (See Figure 4.20).

To put these measurements made in the vicinity of the Buncefield depot in context, they are lower than those typical of near-roadside environments or during Bonfire Night. See Section 4.2 for further exploration of this point.

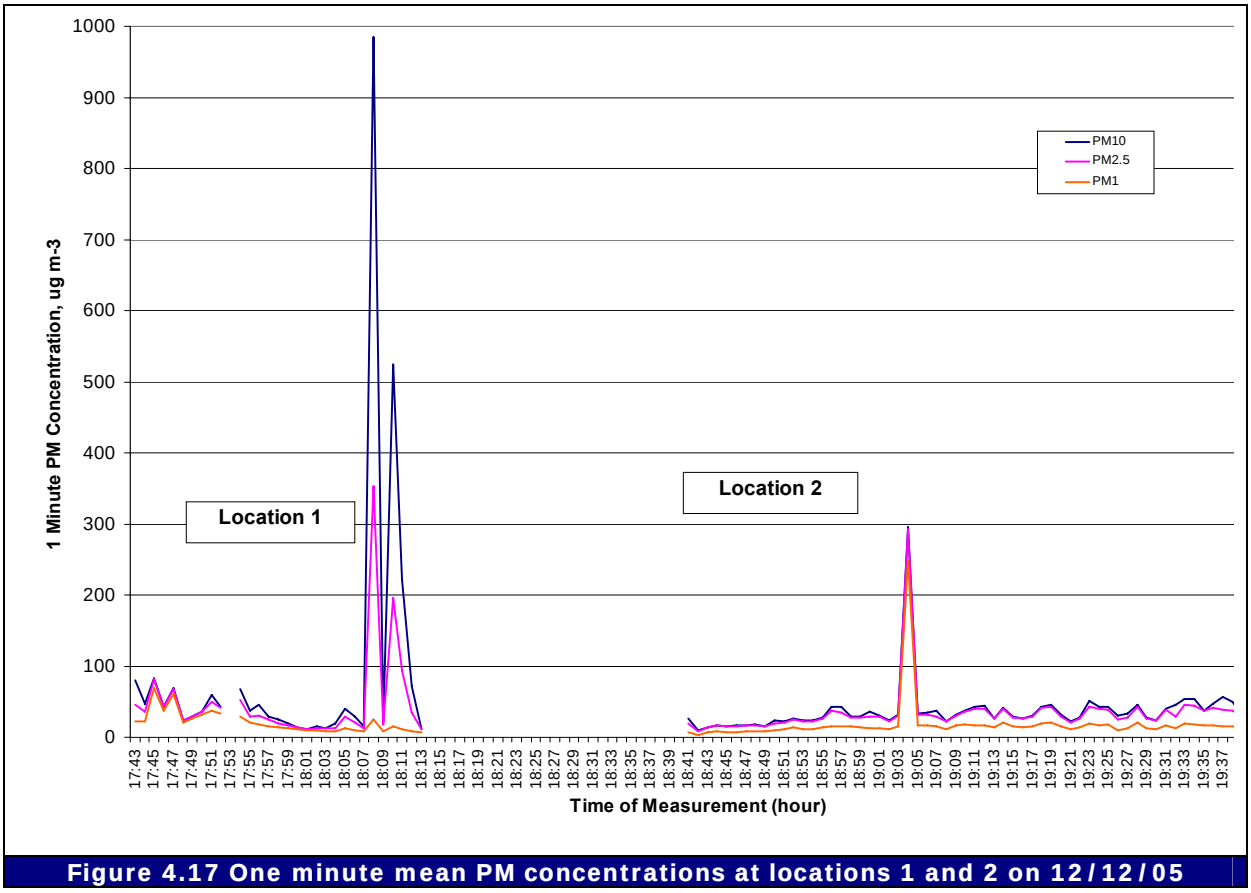


Figure 4.17 One minute mean PM concentrations at locations 1 and 2 on 12/12/05

(Gaps in graphs due to movement of equipment from one location to another)

4.3.2 Volatile Organic Compounds (VOCs)

Netcen also measured VOCs within and outside the oil depot. These were derived from grab sampling, with the samples collected in stainless steel canisters of 1.6 litre volume. The internal surfaces of the canister had been electro polished and passivated by the SUMMA process in order to ensure their inertness. The sampling technique meets the requirement of the USEPA method TO-14A. Air samples in the stainless steel canisters were analysed using a gas chromatograph fitted with flame ionisation detectors (GC/FID).

This monitoring was carried alongside PM sampling (detailed above) between 12th and 14th December. Figure 4.21 shows all the 30-second mean measurements at the six different locations where VOCs were measured (3, 4 and 7 in the oil depot and 1, 5 and 6 outside) - see Figure 4.16 for exact locations.

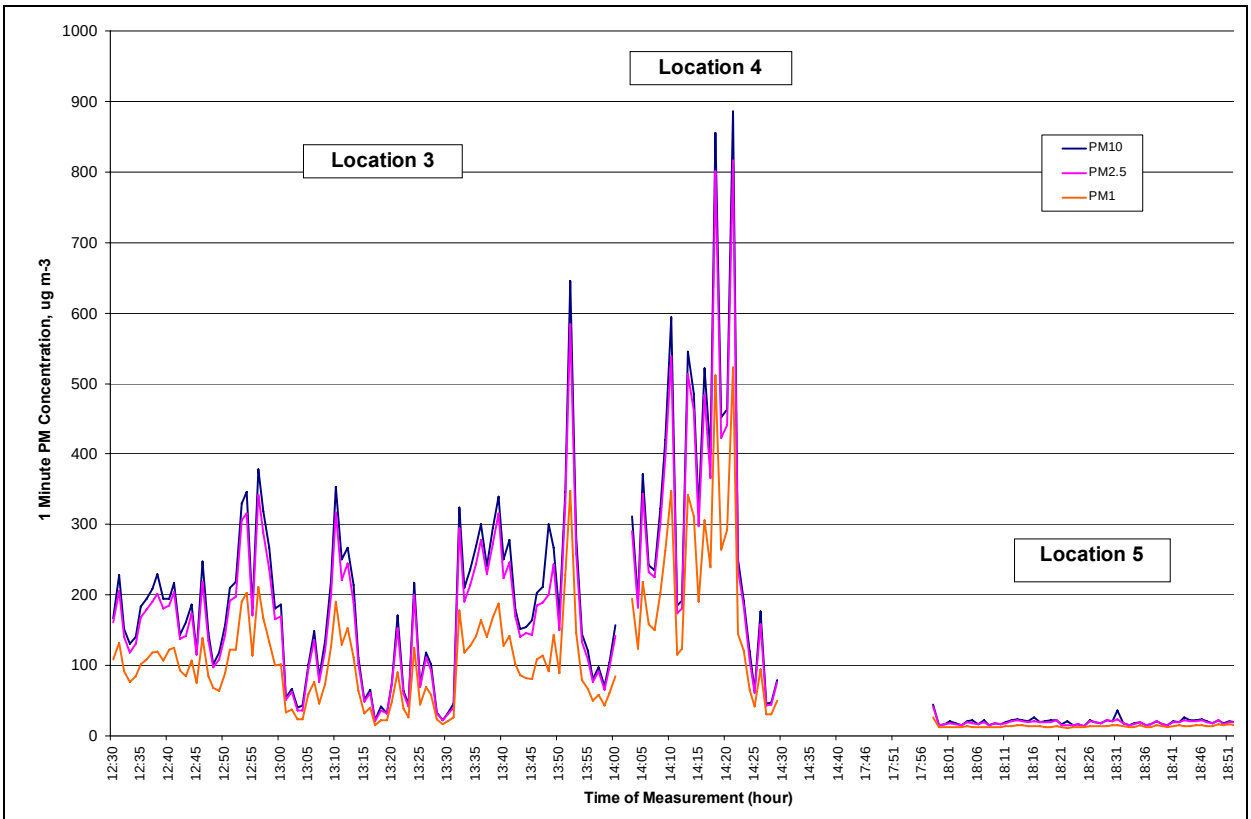


Figure 4.18 One minute mean PM concentrations at locations 3, 4 and 5 on 13/12/05

(Gaps in graphs due to movement of equipment from one location to another)

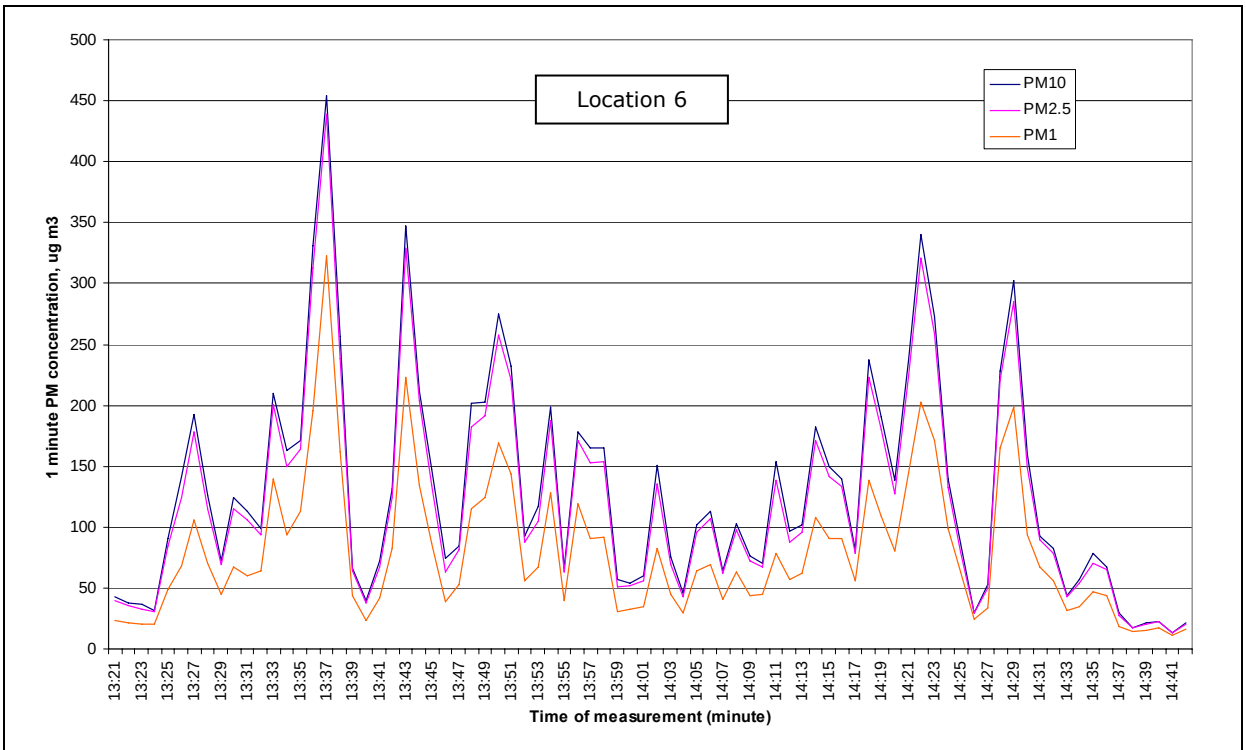


Figure 4.19 One minute mean PM concentrations at location 6 on 14/12/05

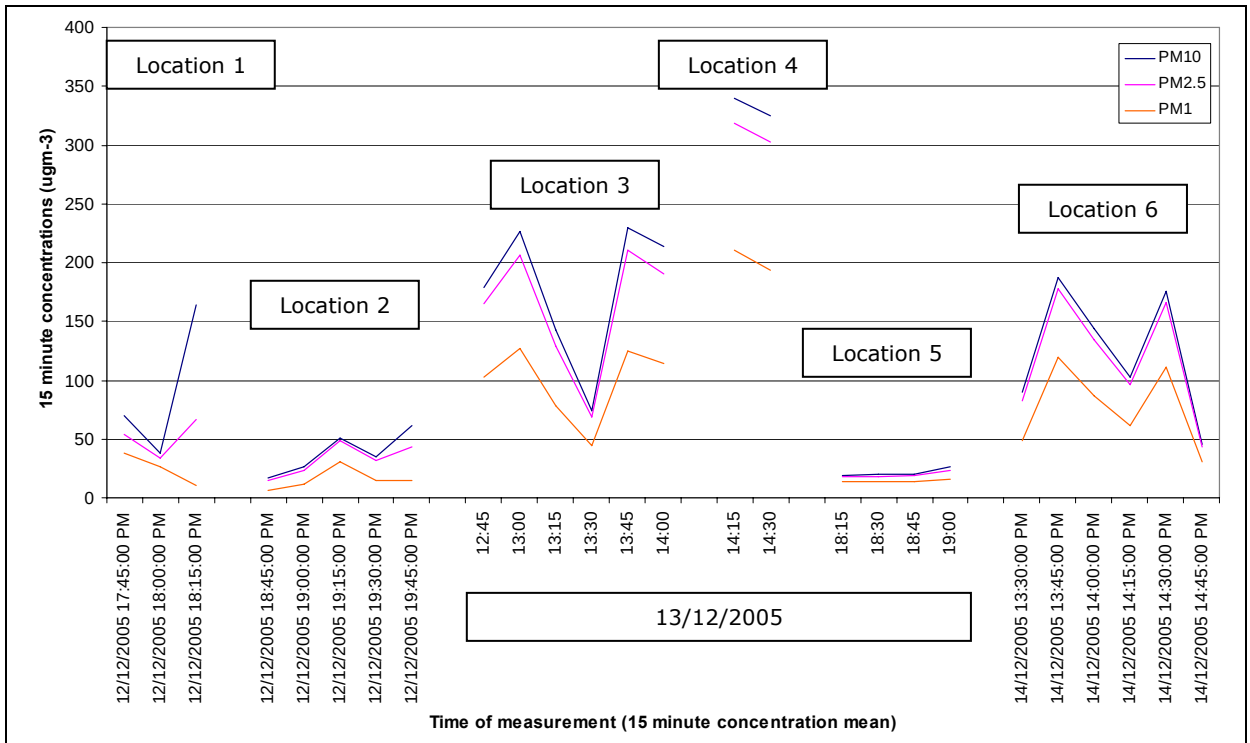


Figure 4.20 15-minute mean PM concentrations between 12/12/05 and 14/12/05

(Gaps in graphs due to movement of equipment from one location to another)

As can be seen in Table 4.2, none of the measured VOC concentrations exceeded any of the short term Environmental Assessment Levels (EALs) for air for the protection of human health[1]. To provide perspective, Figure 4.22 compares the maximum 30 second mean VOC concentrations obtained from grab sampling between 12th and 14th December with maximum hourly measurements at Marylebone Road in 2003 and across the UK Hydrocarbon Network in 2000.

For example, the highest recorded toluene grab-measurements around Buncefield were of the order of 700 μgm^{-3}. By way of comparison, the EAL for this species is 8000 μgm^{-3}.

It may be noted that in Table 4.2 we are comparing 30-second mean measurements from the incident with hourly measurements; we would, of course, normally expect peak 30-second mean measurements to be higher than corresponding hourly measurements due to the shorter averaging period. With the exception of a few pollutants, however, the levels measured at Hemel Hempstead during the Buncefield incident are much lower than those recorded at Marylebone Rd or, indeed, across the hydrocarbon network.

Compared to the usual levels measured across the Hydrocarbon Network, there were increased levels of mp-xylene, oxylene, ethylbenzene, 1,2,3 trimethylbenzene, 1,2,4 trimethylbenzene and 1,3,5 trimethylbenzene surrounding the oil depot (see Figure 4.22). However, these levels are well below the EAL of 37500 μgm^{-3} for the trimethylbenzene and 66200 μgm^{-3} for mp-xylene. High levels of these species are typical of unburnt fuel, indicating that the origin of the pollution is likely to have been evaporative releases from the fuel in the tanks, rather than from the plume itself.

[1] In order to fulfil its emissions regulatory role, the UK Environment Agency has developed environmental criteria known as environmental assessment levels (EALs) for different environmental media (air, water and land) for use within the H1 assessment methodology framework (Guidance on Environmental Assessment and Appraisal of Best Available Technology –BAT). A hierarchical approach has been used to develop EALs. For air, existing standards and guidelines are used as EALs; however, as there are only a limited number of appropriate values, EALs for most substances have been derived from occupational exposure values by the application of a simple safety factor. It should be emphasised that EALs are not protective of Human Health; they are simply guidelines derived from occupational standards.

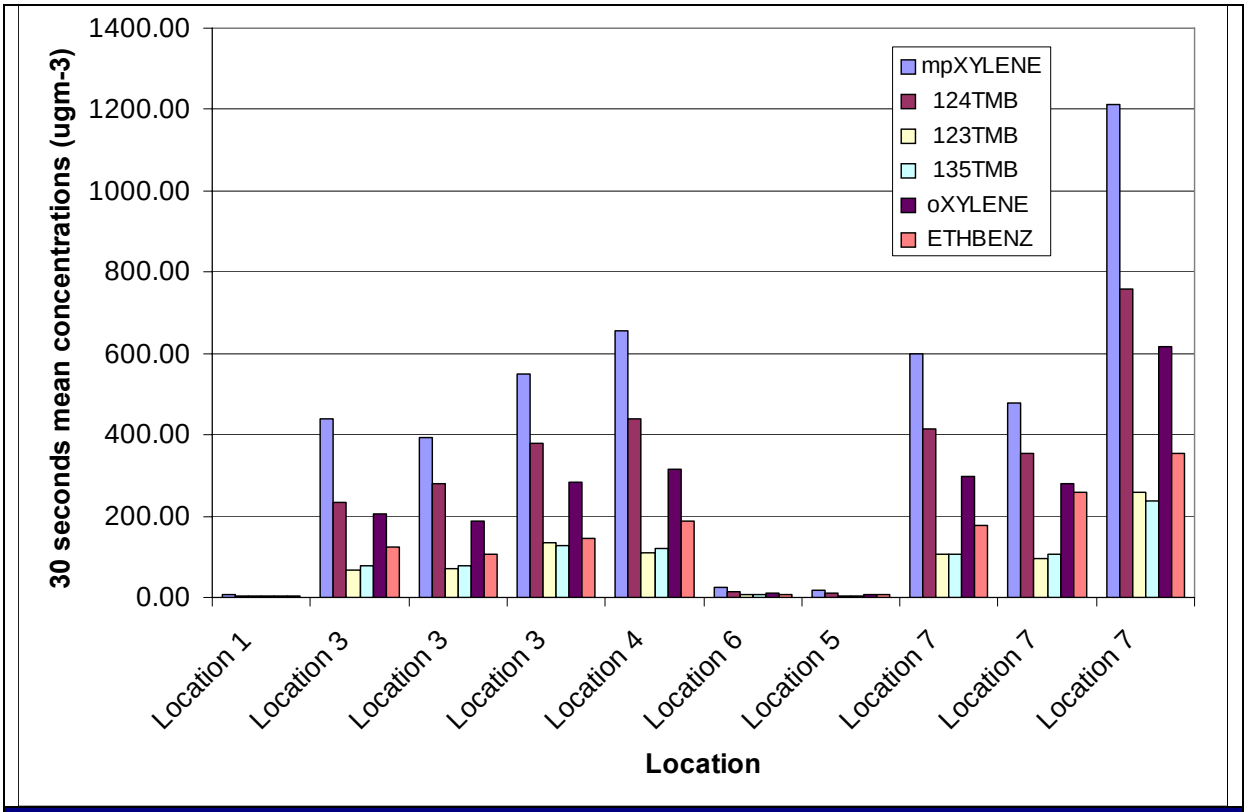


Figure 4.21 30 second mean concentration levels of m+p-xylene, o-xylene, ethylbenzene and three trimethylbenzenes

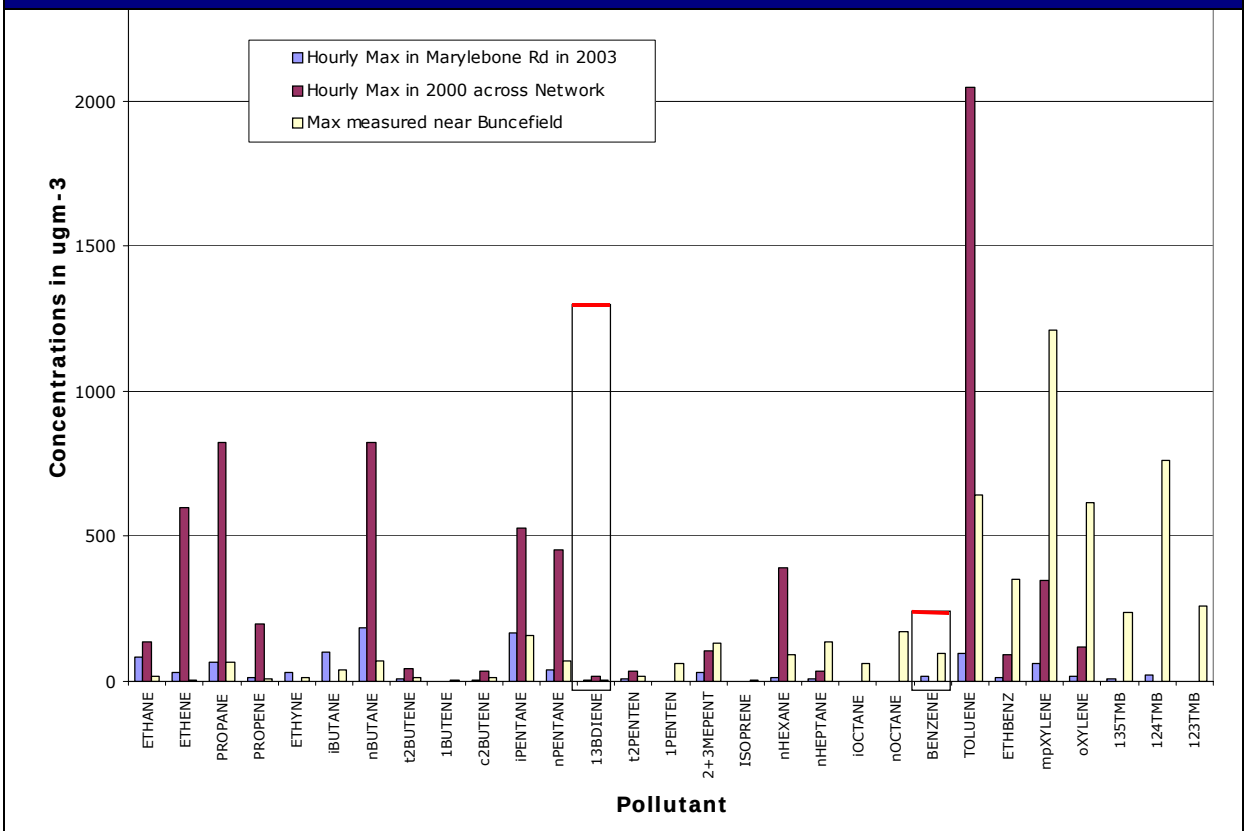


Figure 4.22 Maximum 30 second mean VOC concentrations recorded at the six VOC measurement locations between 12th and 14th December 2005
(Red line represents the short term EAL value if available)

Table 4.2 Volatile organic compound 30 seconds grab sample measurements											
Location	1	3	3	3	4	6	5	7	7	7	Short term EAL*(H1) *15min or 1hour*[7]
Date	12/12/05	13/12/05	13/12/05	13/12/05	13/12/05	13/12/05	13/12/05	14/12/05	14/12/05	14/12/05	
Time	18:00 GMT	11:55 GMT	11:30 GMT	11:40 GMT	13:10 GMT	16:55 GMT	16:42 GMT	12:20 GMT	13:25 GMT	13:35 GMT	
Species (unit)	μgm^{-3}	μgm^{-3}	μgm^{-3}	μgm^{-3}	μgm_{-}^{3}	μgm^{-3}	μgm^{-3}	μgm^{-3}	μgm^{-3}	μgm^{-3}	
mpXYLENE	6.1	440.2	392.2	548.8	655.6	23.3	19.4	599.2	479.8	1211.6	66200
124TMB	4.0	235.4	279.6	380.9	438.2	15.6	10.6	414.6	356.1	760.2	37500
TOLUENE	3.9	345.0	278.5	349.7	477.0	19.1	17.4	344.5	350.0	641.5	8000
oXYLENE	2.3	204.1	186.5	282.9	315.6	9.6	8.1	298.5	279.8	617.8	66200
nOCTANE	1.0	38.9	48.9	171.3	153.0	1.6	0.4	34.8	50.6	63.0	
ETHBENZ	2.0	124.5	106.1	145.5	189.5	7.6	5.7	175.5	260.0	353.9	55200
nHEPTANE	1.1	29.3	45.3	138.5	136.7	1.8	1.2	25.6	41.8	55.1	
123TMB	2.7	68.5	72.6	134.3	111.0	8.2	3.3	106.8	94.6	258.5	37500
135TMB	2.5	79.2	76.6	126.9	119.4	7.4	3.3	107.7	107.3	236.5	37500
BENZENE	1.7	48.8	38.9	97.4	96.0	4.7	4.4	30.1	36.8	54.9	208
2+3MEPENT	1.8	54.6	45.7	86.7	131.7	3.9	3.6	24.2	126.8	62.9	
nHEXANE	1.3	20.8	18.2	78.6	91.2	1.5	1.1	12.3	23.4	26.2	21600
iPENTANE	2.5	55.3	48.7	64.3	156.7	5.6	5.8	25.6	43.4	62.5	
nPENTANE	2.4	22.8	19.8	44.2	72.2	2.4	2.2	11.7	16.9	27.5	
iOCTANE	0.5	31.1	33.6	33.0	53.2	1.3	1.4	22.2	47.5	60.1	
nBUTANE	3.4	35.9	21.8	27.3	70.3	6.7	5.4	17.7	19.1	37.9	181000
iBUTANE	1.7	19.7	10.8	11.9	40.4	3.8	3.2	9.2	11.2	19.9	
ETHYNE	0.9	9.8	6.2	11.6	9.1	2.4	3.7	2.7	1.2	4.2	
1PENTEN	0.4	25.5	21.6	10.4	60.6	2.03	2.2	13.4	33.1	30.0	
ETHANE	3.0	16.3	14.2	10.0	18.1	14.8	11.0	10.3	7.9	15.8	
PROPENE	0.8	8.3	5.8	9.7	7.2	2.8	3.1	2.6	4.3	5.4	
PROPANE	3.6	6.3	5.2	6.4	4.9	5.6	3.7	6.4	64.3	9.0	
ETHENE		3.5	5.2	5.7	4.7	1.9	1.6	2.4	0.8		
t2PENTEN		7.0	7.1	5.2	18.2	0.5	0.3	2.4	2.3	6.3	
13BDIENE		2.3	1.7	3.0	1.7	0.6	0.7	0.6	0.3	1.1	1320
t2BUTENE	1.8	4.5	4.8	3.0	15.3	1.4	1.5	2.3	1.2	6.2	
c2BUTENE	0.8	3.4	3.2	2.3	11.0	1.1	0.4	1.5	1.4	3.8	
1BUTENE	0.3	2.7	2.4	2.1	5.9	0.9	0.8	1.1	0.7	2.4	
ISOPRENE	0.3	4.0	3.8		5.5	0.6	0.4	3.2	1.9	3.8	

** Environmental Assessment Levels for air (for the protection of human health)*

[7] http://www.environment-agency.gov.uk/commondata/acrobat/h1v6_jul03guidance_608809.pdf

4.3.3 Targeted local monitoring by the Fire Brigade's Scientific Advisors and the Health and Safety Laboratories on behalf of HPA

Between 11th and 14th December, the Fire Brigade's Scientific Advisors (Bureau Veritas) carried out air quality monitoring at several locations around the oil depot. Concentrations of CO, CO_2, HF, SO_2, NH_3 and volatile organic compounds (VOCs) were measured. Monitoring over the period 12th, 13th, and 14th December indicated no significant increase in concentrations of CO, CO_2, HF, SO_2, NH_3 or VOCs. Please see Appendix H for further detail.

Particulate monitoring showed short-term peak concentrations between 40 μgm^{-3} and 1300 μgm^{-3} maximum on Monday and Tuesday, respectively.

4.3.4 The FAAM Aircraft

The Facility for Airborne Atmospheric Measurements (FAAM) BAe146-301 aircraft, operated jointly by the Met Office and NERC, flew on the 12th and 13th December to study the position and composition of the plume. The key flight was on 13th December (flight identifier B149), which took place between 11:59 am and 4:10 pm and included runs in the plume at a distance of around 78km from the source and directly overhead the Buncefield site (see Figure 4.23). Images of the exterior and interior of the FAAM aircraft appear as Figures 4.24 and 4.25.

The aims of the flights were:

1) To provide real-time information on the position of the plume to the Met Office Environment Monitoring and Response Centre (EMARC) and
2) To provide the only *in-situ* data on the chemical composition of the elevated smoke plume. The aerosol size distribution was measured with a Passive Cavity Aerosol Spectrometer Probe, which is capable of measuring aerosol particles between 0.1 and 3 microns diameter.

The chemical composition of particles was measured using an Aerosol Mass Spectrometer operated by Manchester University. Two sets of quartz filters were exposed to the smoke plume and analysed after the flight by Harwell Scientifics and the Health and Safety Laboratory (HSL) Buxton.

The first set of filters (Exposures 1 and 2) was analysed by Harwell Scientifics; these filters were exposed during aircraft runs 2 to 6 of the flight between 12:46 pm and 2:36 pm at a range of altitudes in and above the smoke plume, and at a distance approximately 78 km downwind from the source. The second set of filters was exposed during aircraft runs 7 to 14 between 2:47 pm and 3:56 pm and was sent to HSL, Buxton for analysis. This set consisted of two filters; one which sampled the plume at a height of 1010 m at a distance 78 km downwind from the source (Exposure 3) and one which was exposed at a range of altitudes in and above the smoke plume directly over the Buncefield site (Exposure 4).

Analysis of data gathered by the Aerosol Mass Spectrometer and other instrumentation on the aircraft showed that Poly Aromatic Hydrocarbons (PAHs) were not measured at any time during the flight and that the main constituent of the plume was black carbon (soot).

The measurement of PM_{10} is not possible from an aircraft. Using the size distribution data gathered during the penetrations of the smoke plume directly overhead Buncefield, it is possible to estimate $PM_{2.5}$ (i.e. the total mass of particulates of mean aerodynamic diameter of 2.5 μm). This estimation requires knowledge of the refractive indices of the particles and their density in order to convert the size information to a mass.

Using a range of values of refractive index and density from the published literature for black carbon, the $PM_{2.5}$ mass averaged over a 7.4 km (69 second) run up the plume and directly over the source was 461 μgm^{-3}, with an uncertainty ranging from 300 to 576 μgm^{-3}. Directly over the source, the plume was measured at altitudes between 500 m and 700 m. The plume was not detected in a run at 930 m altitude over the source region. During the downwind runs (~78.2 km downwind), the plume was intersected at altitudes between 500 m and 1470 m. It was not detected during runs at 1750 m or 2500 m; at a distance of ~78.2 km from the source, the plume was already approximately 10 km wide.

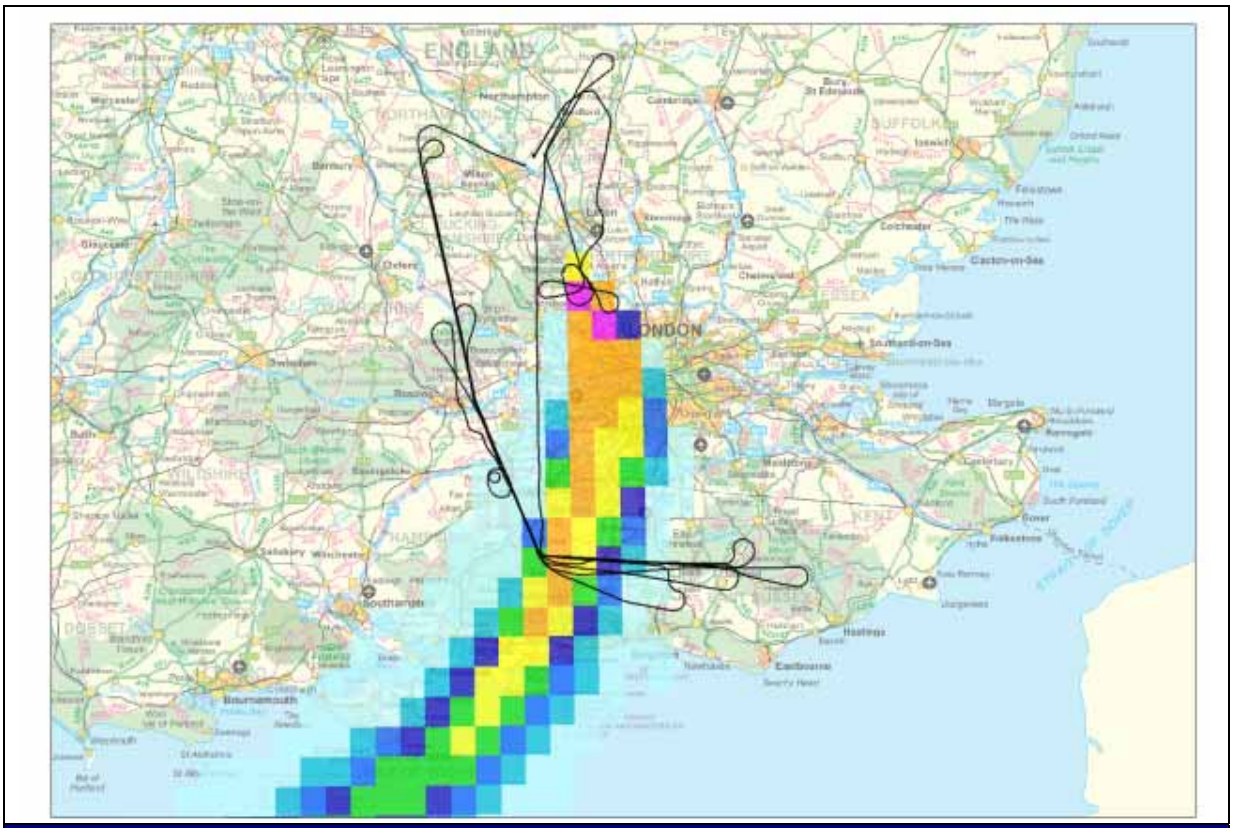


Figure 4.23 FAAM aircraft flight path on 13/12/05 and the NAME-predicted plume

4.3.4.1 Dioxins, Furans and PCBs from the FAAM aircraft monitoring

Appendix A includes a letter report from Netcen, based on analyses provided by Harwell Scientifics, on levels of dioxins, furans and PCBs from air samplers from the FAAM aircraft. These three samples consisted of a blank and samples taken during Exposures 1 and 2, which sampled air both within and outside of the plume ~78 km downwind of the source. No PCBs were detected in any of the three samples.

The letter report provides estimations of inhalation exposure that would result from the measured concentration of polychlorinated dibenzodioxins and dibenzofurans (PCDD/Fs) and PCBs. The Committee on Toxicity of Chemicals in Food, Consumer Products and the Environment's (COT) Tolerable Daily Intake (TDI, based on the total body burden) for children was only slightly exceeded by the concentrations measured by the FAAM aircraft. The report concludes that, unless exposure at these concentrations is prolonged, there would only be a slight impact on body burdens.

Analysis of levels of dioxins, furans and PCBs in air samples from Exposures 3 and 4 was not possible due to the extraction method used by HSL, Buxton.

4.3.4.2 PAHs from the FAAM aircraft monitoring

Figure 4.26 shows the PAHs levels measured from Exposures 1 - 4. Concentrations are generally low. Focusing on B[a]p (Benzo[a]pyrene), the levels found in Exposure 1 (0.012 ngm^{-3}) and 2 (0.046 ngm^{-3}) are low for this time of year. In 2004, the level for the 4th quarter was 0.17 ngm^{-3} in London and at the rural site of Stoke Ferry < 0.06 ngm^{-3}. These levels appear typical of what is seen in spring to autumn.

Results for Exposures 3 and 4 were <0.1 and 0.4 ngm^{-3}, respectively. Exposure 4 (sampled directly over the Buncefield site) is at the lower assessment threshold of the Air Quality 4th Daughter Directive. Target values in the Directive for B[a]P are based on annual average concentrations. However, concentrations between October and March are typically higher than summer levels. This concentration is above the typical quarter 4 levels found at the London site and Stoke Ferry, a rural location. These levels are broadly typical of some of the UK's industrial monitoring sites.

Figure 4.24 The FAAM Aircraft used for plume monitoring

Figure 4.25 Inside the FAAM

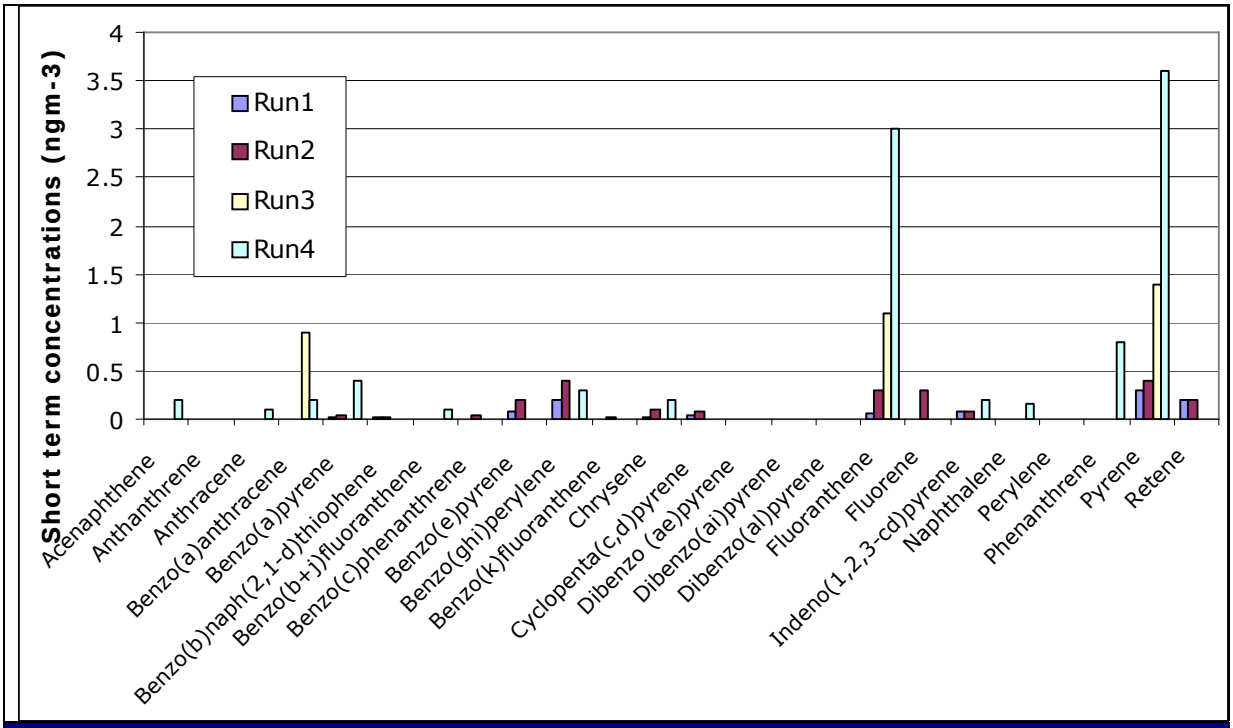


Figure 4.26 PAH measurements from the FAAM aircraft

Levels of pollutants in the plume were within normal concentrations seen at other monitoring sites. It is possible that this is the result of the high combustion temperatures associated with such a large-scale fire, or the high quality of the refined fuel being burnt.

Overall, we see that a wide range of measurements, presented in this section, confirm that the Buncefield event did not appear to result in large ground-level air quality impacts over local, regional or national scales. Elevated pollution levels across a number of monitoring networks in Southern England were within normal ranges measured throughout the year.

The possibility of high concentrations of ground level pollution from the Buncefield explosion and fire cannot be totally ruled out; however, any such peaks were likely to have been localised and of a transient nature. Some of the observations highlighted in previous sections – specifically those for Horsham, Lewes Roadside and Marylebone Road – indicate the possible duration and extent of such events. However, it should be noted that none of these isolated instances can be definitively attributed to Buncefield.

5 Analysis of Air Trajectories

Airmass Trajectories are simple linear representations of large-scale air movements in the atmosphere. Although they are relatively easy to understand and to visualise, they do not take into account the effects of turbulent mixing and therefore do not show the full range of air movements possible. Back-trajectories show how air masses may have been transported prior to reaching their destination, whereas forward-trajectories show the movement of air after leaving its origin.

To assist daily air quality forecasting in the UK, *1000 mB 96-hour Forecast Air Back-Trajectories* are produced and used on a daily basis for Netcen's Trajectory Ozone Model. This model uses output from the Met Office's numerical weather prediction models as its input, and predicts how air masses have been transported to the UK over the preceding 96 hours. The global version of the Met Office's numerical weather prediction model (the Unified Model) is used with a horizontal resolution of 40 km at mid-latitudes. The forecast back-trajectories provided were used during the Buncefield event to gain a fuller understanding of the possible plume movements, as well as understanding the amount of re-circulation over the UK. Airmass back trajectories at midday from the 9th to 16th of December are presented below in Figures 5.1 and 5.2.

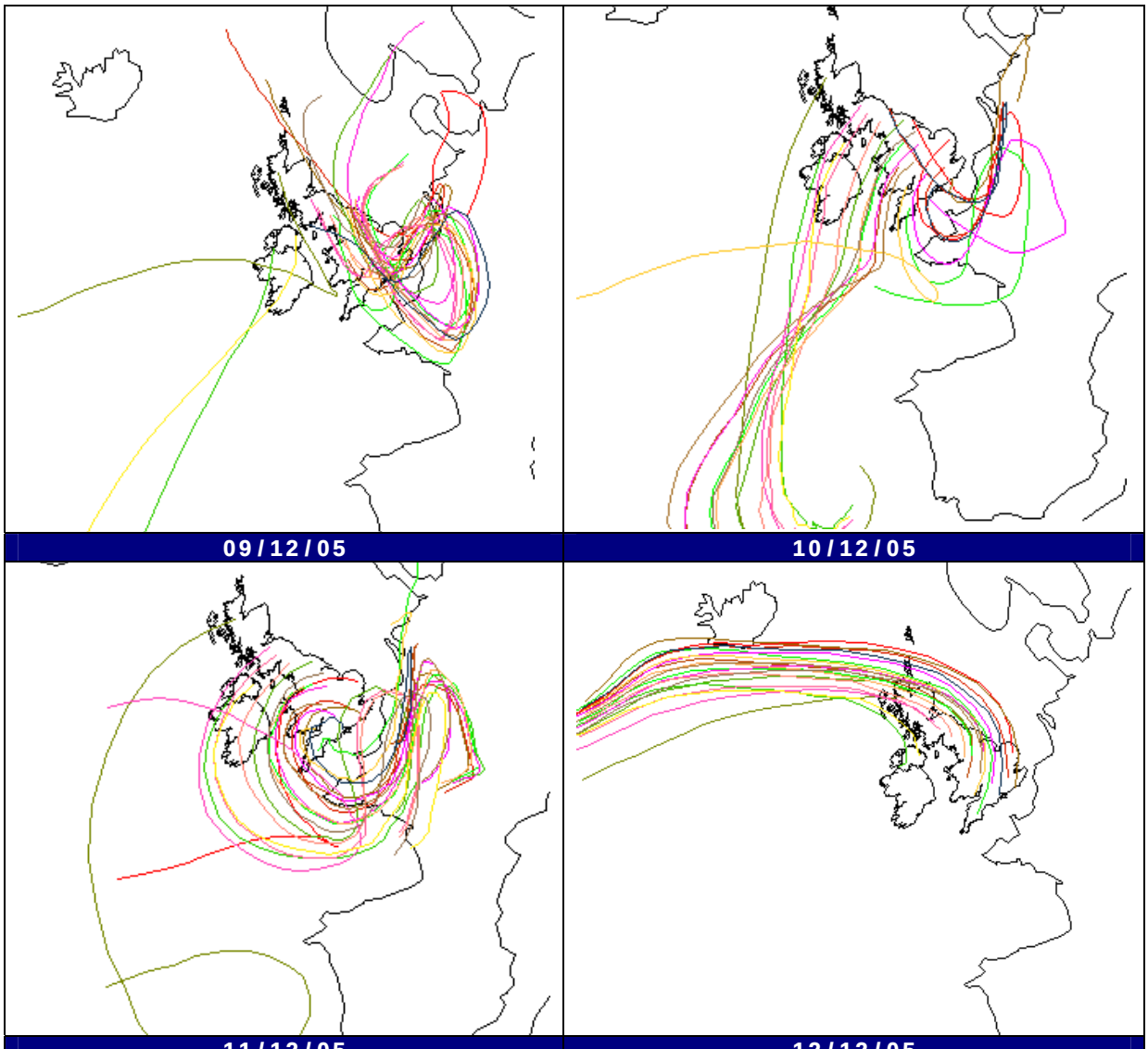
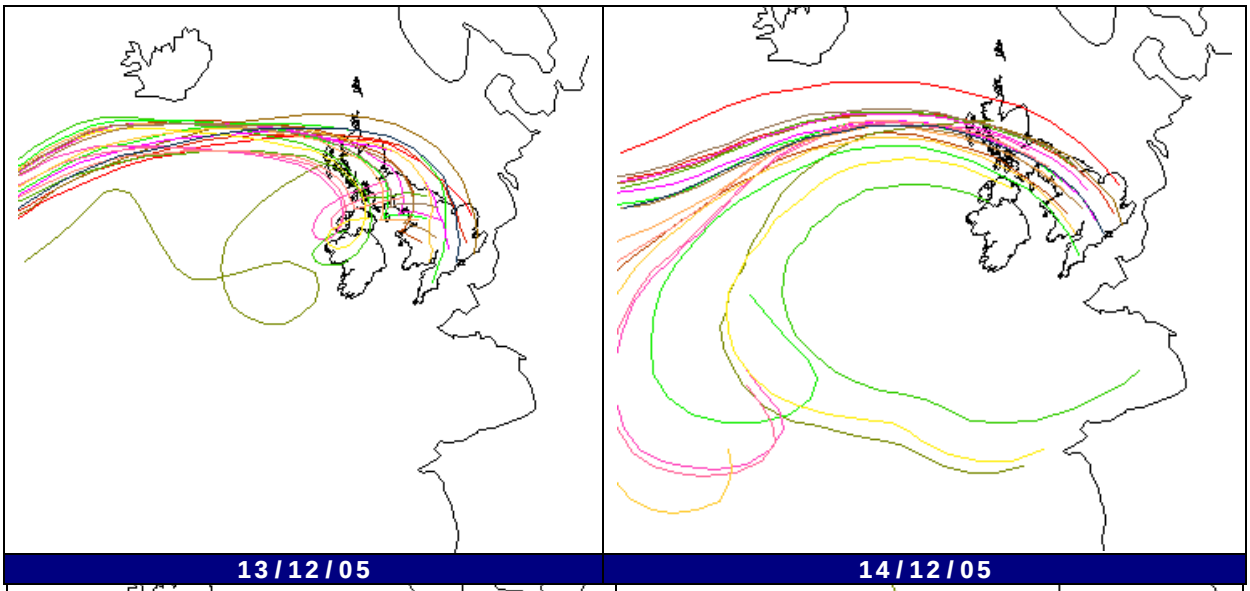


Figure 5.1 Air back trajectories between the 9th and 12th December 2005

The 96-hour back-trajectories show that the weather pattern changed on Monday 12th December. Up until Monday 12th, the pattern was characterised by re-circulation of air over southern England and northern France. This was due to the dominance of a high pressure system. Following the passage of a front during the morning of Monday 12th, back trajectory analysis suggests that air masses affecting the UK were originating over the Atlantic. Winds were from a northerly to north-easterly direction over the Hemel Hempstead area.



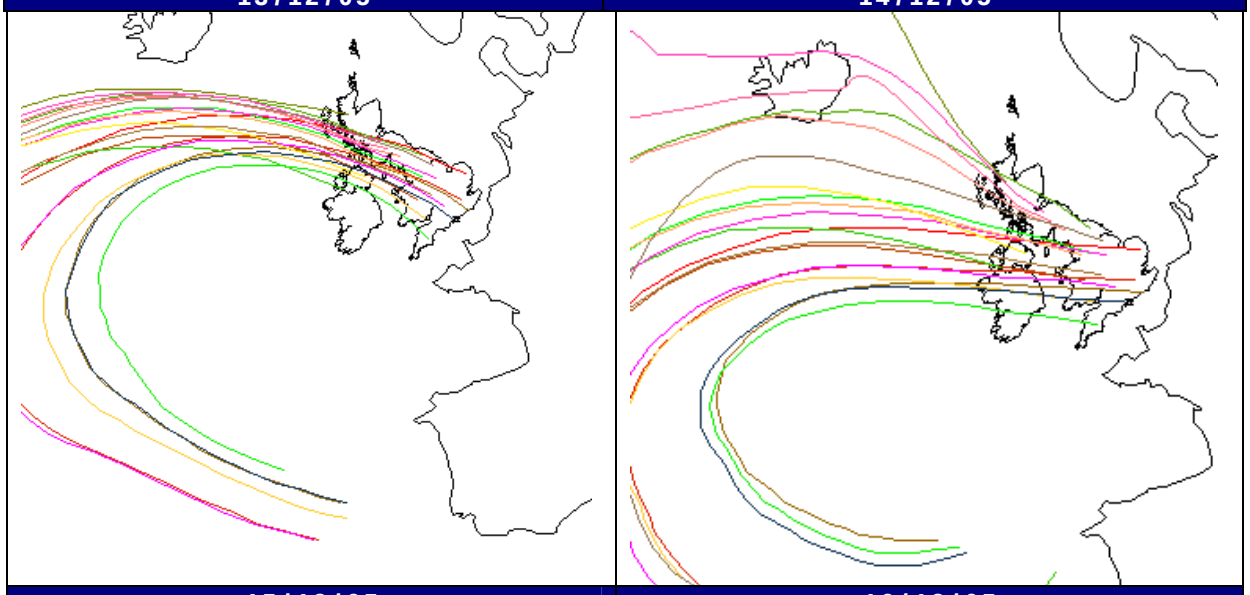


Figure 5.2 - Air back trajectories between 13th and 16th December 2005

6 Met Office Plume Modelling

Using its well-established NAME dispersion model, the Met Office undertook systematic modelling of the large-scale plume from the Buncefield fires. This was carried out both during and after the event. The Met Office's atmospheric dispersion model NAME (Numerical Atmospheric dispersion Modelling Environment) has a wide range of applications including air quality forecasting, predicting the transport of airborne substances and identifying source locations. It is a Lagrangian model driven by either three-dimensional meteorology or single-site meteorological data (e.g. from observations), with turbulent dispersion simulated using random walk techniques[1].

In modelling the plume from the Buncefield oil depot fire, three-dimensional meteorological data from the mesoscale version of the Met Office's numerical weather prediction model (the Unified Model) were used with a horizontal resolution of approximately 12 km. There was (and still is) a large degree of uncertainty in the source release details and, consequently, a number of assumptions based on the available observations were adopted. These assumptions have been revised and refined following the event, taking into account all available estimates and observations. The modelling results presented in this report are based on our best estimates at this time of the worst-case scenario (100% of 105 million litres burnt) and are broadly similar to those issued during the event.

Due to the intense heat of the fire, the plume was highly buoyant and rose rapidly and vertically within the atmosphere. The large amount of vertical wind shear present on 11/12/05 enabled the height attained by the plume to be estimated by comparing NAME output with satellite imagery. This suggested that the plume reached a height of 3000 m above ground level on 11/12/05. Visual observations and modelling of the plume with NAME suggest that most of the plume remained trapped above the boundary layer (the lowest part of the atmosphere which is directly influenced by the ground) on Sunday 11th December.

Material entering the boundary layer will, in general, be mixed fairly rapidly within NAME. Hence the predicted boundary layer concentrations can be taken to be representative of predicted ground level concentrations. Boundary layer concentrations of PM_{10} predicted over southeast England and into northern France on Sunday 11th December were low. On Monday 12th December, higher PM_{10} boundary layer concentrations were predicted over the UK (to the south-west of the oil depot) and over the Channel and northern France. However, the monitoring networks across France did not record elevated levels during the incident.

Figure 6.1 presents hourly averaged fields of PM_{10} concentrations over a height range between 0 and 4000 m above ground, at 12:00 pm on 11/12/05 and at 1:00 pm on 12/12/05. The results in Figure 6.1 are in good agreement with satellite imagery shown in Figure 2.2 and Figure 2.3. Predicted boundary layer PM_{10} concentrations, which can be taken to be representative of predicted ground level concentrations, are presented in Appendix E.

A more detailed technical account of the Met Office modelling and research into the Buncefield oil depot event is presented in Appendix E, together with the results and analysis of NAME outputs. Please see Appendix H, also.

Taken together, the back trajectories presented in Section 5, together with the modelling results in this section (and Appendix E) shed considerable light on the monitoring results reviewed in Section 4.

Despite the very large quantities of pollutants emitted, particularly particulate matter (see Section 3), a wide range of air pollution monitoring undertaken before, during and after the event showed that UK ground-level concentrations of a wide range of pollutants remained low to moderate over local, regional and national scales. Although there was limited evidence of sporadic and episodic plume grounding on occasions, it appears that the high plume buoyancy and favourable meteorological conditions resulted in the overwhelming bulk of the pollution being trapped aloft, with minimal mixing to the ground. As a result, we have seen little evidence of widespread or significant air quality impacts at ground level due to the pollutants emitted from the Buncefield fires.

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[1] Jones A.R., Thomson D.J., Hort M. and Devenish B., 'The U.K. Met Office's next-generation atmospheric dispersion model, NAME III', in *Air Pollution Modelling and its Application XVII*, Kluwer Academic Publishers, 2006.

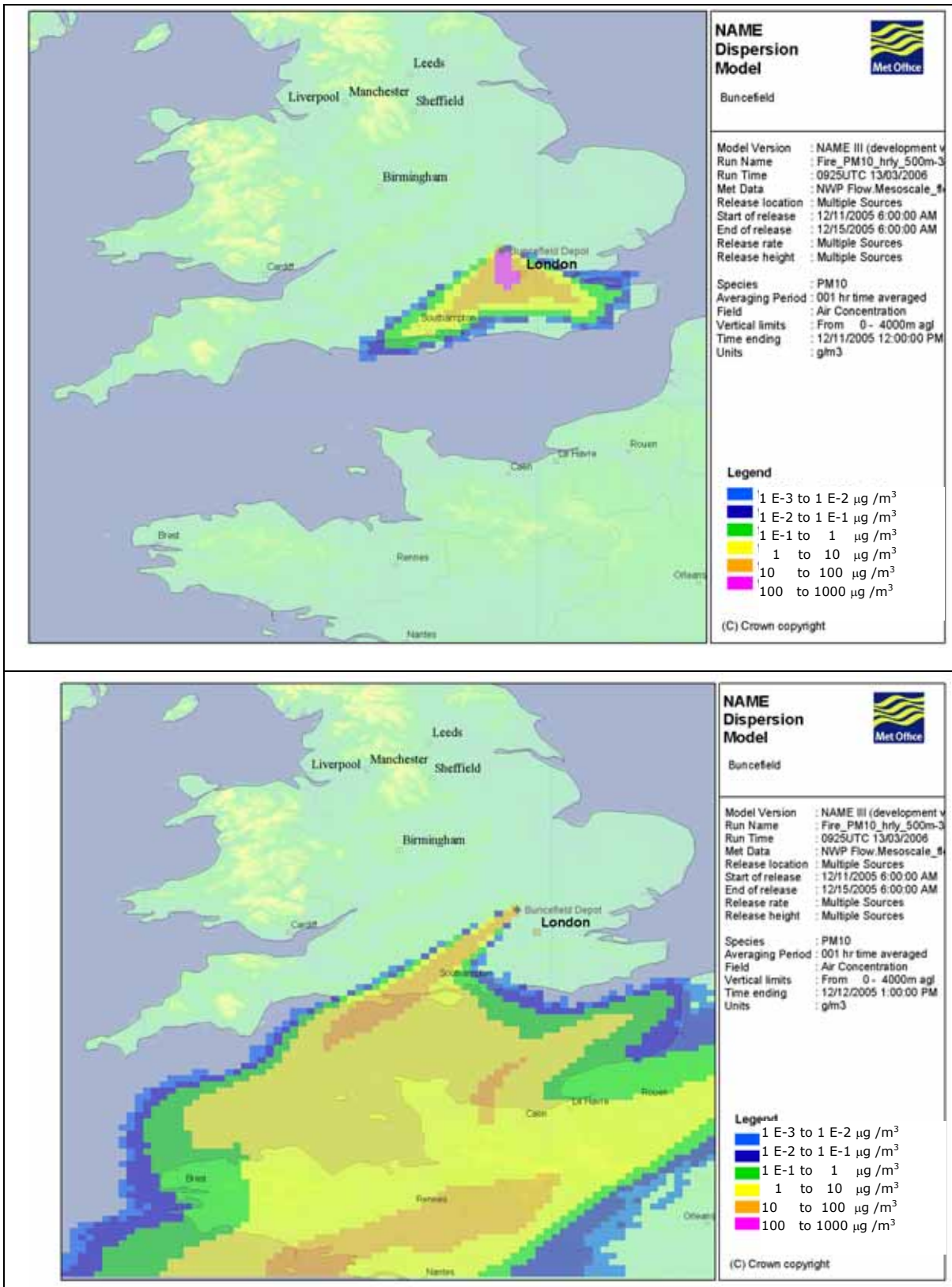

Figure 6.1 NAME predicted hourly averaged PM_{10} concentrations between 0 and 4000 m at 12:00 pm on 11/12/05 (top) and at 13:00 pm on 12/12/05 (bottom)

7 Conclusions

On Sunday 11th December 2005, there was a major explosion at the Buncefield oil depot near Hemel Hempstead, north of London. Following the explosion, large stocks of petrol, aviation turbine fuel, diesel and gas oil at the depot remained on fire until Wednesday 14th December. Calculations based on the National Atmospheric Emissions Inventory indicate that large quantities of particles and other pollutants may have been emitted during this period.

Air quality monitoring undertaken on-site and involving several measurement networks across southern England showed no widespread increase in ground-level air pollution concentrations during this period. In particular, provisional levels of air pollution measured within the national Automatic Urban and Rural Network (AURN) did not – with a few noted exceptions which were demonstrably not related to the Buncefield event - exceed the 'Low' air pollution category as defined for ambient air quality reporting in the UK.

In general, local monitoring networks across the southeast of England also measured low levels of air pollution throughout the event. Two stations in the Sussex Air Network - Horsham Roadside and Lewes Roadside – showed excursions into the 'Moderate' air quality index band (consistent with mild health effects in sensitive individuals). In the case of Horsham roadside site, it appears that the elevated levels might not be wholly traffic pollution-related; subsequent modelling suggests that the elevated levels here may have been partly due to plume grounding. Even so, measured concentrations remained well within normal ranges.

Not surprisingly, the highest pollutant concentrations related to the event were recorded during targeted local monitoring in and around the depot itself. However, even these levels were not significant when compared to typical PM_{10} and VOC concentrations that might be expected during UK-wide pollution episodes or due to localised events such as bonfires, idling vehicles or construction work.

Some elevated hydrocarbon levels were measured inside the depot; these were probably due to evaporative emissions from unburnt fuel rather than from direct plume impacts. Hydrocarbon concentrations at Marylebone Road were not unusually high. There were, however, some unusual observations – specifically, elevated ratios of some species with respect to benzene – at this roadside location; these cannot be simply or readily explained.

The Met Office undertook modelling of the large-scale plume from the fires. This showed that most of the plume remained trapped above the boundary layer (the part of the atmosphere interacting directly with the ground) on Sunday 11th December. Predicted boundary layer concentrations of PM_{10} over southeast England and into northern France, which can be taken to be representative of ground level concentrations, on this day were low. On Monday 12th December, higher PM_{10} boundary layer concentrations were predicted over the UK (to the south-west of the oil depot) and over the Channel and northern France. However, the monitoring networks across France did not record elevated levels during this day or the incident as a whole.

A fully instrumented aircraft made extensive measurements of the position and chemical composition of the smoke plume on the 13th December. These observations were broadly consistent with model predictions and showed that the plume consisted mainly of black carbon - soot.

A wide range of measurements confirm that the Buncefield fires did not appear to result in large ground-level air quality impacts over local, regional or national scales. Elevated pollution levels across the monitoring networks were within normal ranges measured on other occasions. Whilst it cannot be ruled out that the plume may have grounded in areas not currently covered by the monitoring networks, any resulting peaks were likely to have been localised and of a transient nature.

Why did such a major explosion and fires not result in greater air pollution impacts? Both the monitoring and modelling suggest that the high buoyancy of the plume resulted in the bulk of the emissions being trapped aloft, above cold, stable layers of the lower atmosphere. Because of this, the emitted pollutants came only sporadically into contact with the ground.

It is likely that corresponding ground level air pollution impacts would, however, have been far higher had this event occurred in the summer months, when the lower atmosphere is more turbulent and well-mixed.

8 Acknowledgements

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