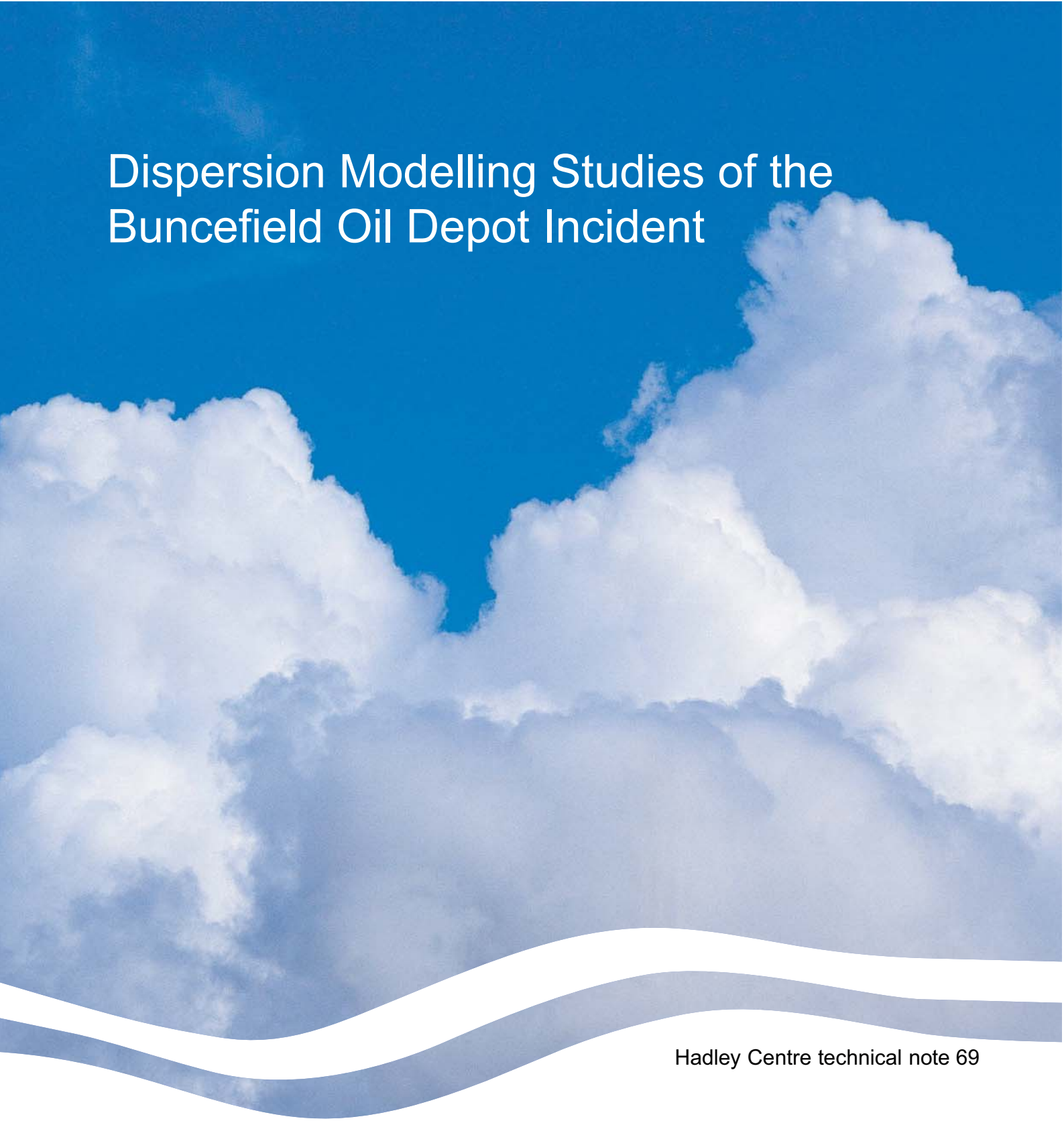
Dispersion Modelling Studies of the Buncefield Oil Depot Incident



Hadley Centre technical note 69

Helen N Webster, Steven J Abel, Jonathan P Taylor, David J Thomson, James M Haywood and Matthew C Hort

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Met Office

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Extended abstract

The explosion at the Buncefield Oil Depot on the morning of Sunday 11th December 2005 resulted in the largest peacetime fire in Europe to date. During the event, the Met Office contributed to the emergency response by predicting the transport and spread of the large smoke plume using atmospheric dispersion models, by issuing meteorological information and by taking in-situ measurements from within the plume using the Facility for Airborne Atmospheric Measurements (FAAM) aircraft. In this report we describe the emergency response work undertaken by the Met Office at the time of the event together with further in depth plume modeling studies which have subsequently been carried out. We also discuss in detail measurements taken from within the plume by the FAAM aircraft and the meteorological situation during the event. The FAAM aircraft, a converted BAe146-301 jointly funded by the Met Office and NERC, *made a number of passes through the plume at various heights on Tuesday 13th December at a distance of approximately 78 km downwind of the source and directly over the source. Measurements taken from within the plume showed that the plume consisted mainly of black carbon (soot) with low, unexceptional levels of other pollutants (CO, O_3, SO_2, NO_x and hydrocarbons). Highest particle concentrations were measured near to the source. Here estimates of $PM_{2.5}$ concentrations were calculated to be 461 µg m^{-3} with an uncertainty ranging from 290 to 572 µg m^{-3}.*

Estimates of pollutant emissions from the fire, calculated from estimates of fuel on site and in plume measurements, were used to provide more realistic modelling of the plume than was possible in the initial response. On Sunday 11th December, the plume was present mainly above the boundary layer (the lowest part of the atmosphere which is directly influenced by the ground) with low boundary layer concentrations. Using the atmospheric dispersion model NAME, the maximum predicted hourly average PM_{10} boundary layer concentration for the worst case scenario (assuming all fuel on site burnt) was 151 µg m^{-3} and occurred near to the source at 04Z on Wednesday 14th December 2005.

NAME has also been used to determine the origin of near surface air at locations where it has been suggested that grounding of the plume was observed. Peaks in PM_{10} concentrations at a number of measurement sites across the south-east of the UK were identified and the history of near surface air contributing to these peak measurements since the time of the explosion at Buncefield were identified by running NAME backwards from the location and time of the PM_{10} peak. This suggests that the Buncefield plume did not contribute to peaks in PM_{10} concentrations at Lewes and Dorking, but could have contributed to peaks in PM_{10} concentrations at Horsham and St Albans on the evening of Sunday 11th December.

Advanced modelling of the Buncefield plume using NAME is presented in which estimates of the heat released have been used to model the initial rise of the plume due to its high buoyancy using the NAME plume rise scheme. The predicted vertical

spread of the plume was insufficient compared with that observed and, in particular, the predicted plume top is too low. The potential reasons for this are discussed and include the complexity of the Buncefield plume resulting from many tanks on fire, lofting of the plume due to absorption of solar radiation by the black carbon, release of latent heat from condensation of water vapour and an inaccurately modelled temperature profile.

The report concludes with a study of the predicted ground level effects if the Buncefield incident had occurred at another time of the year in different meteorological conditions, namely windy and convective conditions. In addition, comparison is made with the predicted ground level effects if the fire had been allowed to burn uncontrolled for a number of days (i.e., if no fire fighting activities had taken place). This confirms that meteorological conditions on Sunday 11th December were extremely favourable, trapping most of the plume aloft and resulting in low boundary layer concentrations on this day. In comparison to the maximum predicted boundary layer concentrations for the actual event, higher boundary layer concentrations are predicted if the fire had been allowed to continue to burn uncontrolled for 7 to 10 days and in windy and convective meteorological conditions. Peak hourly averaged boundary layer concentrations were up to twice as high as those predicted for the actual event. Predicted deposition fields from the Buncefield incident and from a period with significant precipitation were compared. During the incident there was very little precipitation and hence wet deposition was minimal. The total deposition, during the period of significant precipitation, was dominated by wet deposition and was predicted to be six times greater than that of the actual event.

1 Introduction

1.1 The incident

An explosion occurred at the Buncefield oil depot in Hemel Hempstead, Hertfordshire, UK (51.76ºN 0.429ºW) just after 06Z on Sunday 11th December 2005. The explosion was heard over a wide area and as far away as the Netherlands, a distance of some 200 miles. The subsequent blaze was the largest industrial fire in Europe to date and is thought to have been caused by ignition of a flammable mixture from a leak from a petrol storage tank [1]. Eye witness reports and CCTV footage show a visible mist thought to be due to a fuel leak. Forty three people were injured in the explosion, one seriously. There was significant damage to local homes and offices and around 2000 people were evacuated.

At the height of the blaze, 20 large fuel storage tanks at the oil depot, operated by Total and Texaco, were on fire. Each tank was reported to hold up to 3 million gallons of fuel (unleaded, super-unleaded, motor spirit, gas oil, ultra low sulphur diesel and jet fuel). During Sunday 11th December, no efforts were made to bring the main fire under control, as fire crews assessed the situation, determined the best way to tackle the event and assembled fire fighting equipment. On Monday 12th December 2005, serious efforts to cool and then extinguish the fire with foam and water were undertaken by the fire brigade. The main fire was rapidly extinguished during Tuesday 13th and Wednesday 14th December 2005.

1.2 Response by the Met Office

The Met Office's Environmental Monitoring and Response Centre (EMARC) provides an emergency response service 24 hours a day, 7 days a week. EMARC first became aware of the incident at 07:30Z on Sunday 11th December. During the incident, EMARC provided advice and responded to enquiries throughout. Their role included issuing CHEMETs and NAME model output predicting the spread of the smoke plume, providing weather forecasts and satellite pictures and collating observations. The atmospheric dispersion group were also involved in more extensive modelling of the plume using NAME and the observations based research section took gas and aerosol measurements from within the plume using the Facility for Airborne Atmospheric Measurements (FAAM) aircraft.

2 The event as it unfolded

2.1 Sunday 11th December, 2005

A high pressure system dominated the weather over the south of the UK during Sunday 11th December 2005 (see Figure 1). A stable atmosphere existed, which suppressed vertical mixing. Temperature profiles from radiosonde ascents at Herstmonceux (50.900ºN, 0.317ºE) are shown in Figure A.5 (Appendix A). At 00Z, a shallow strongly stable layer with temperature increasing with height (a temperature inversion) existed at the ground up to a height of about 100 m. Above this layer up to a height of about 400 m above ground, the atmosphere was approximately neutral in stability. Above this neutral layer the atmosphere was stable throughout with a strongly stable layer up to about 1200 m. At 12Z, a shallow neutral layer existed at the ground (~100 m in depth). The atmosphere was stable above and was strongly stable up to height of about 1900 m with a number of small temperature inversions. There was also significant wind shear on Sunday 11th December, with a north-westerly wind at lower levels and a north–easterly wind at higher levels. The meteorological situation during the incident is described in greater detail in Appendix A.

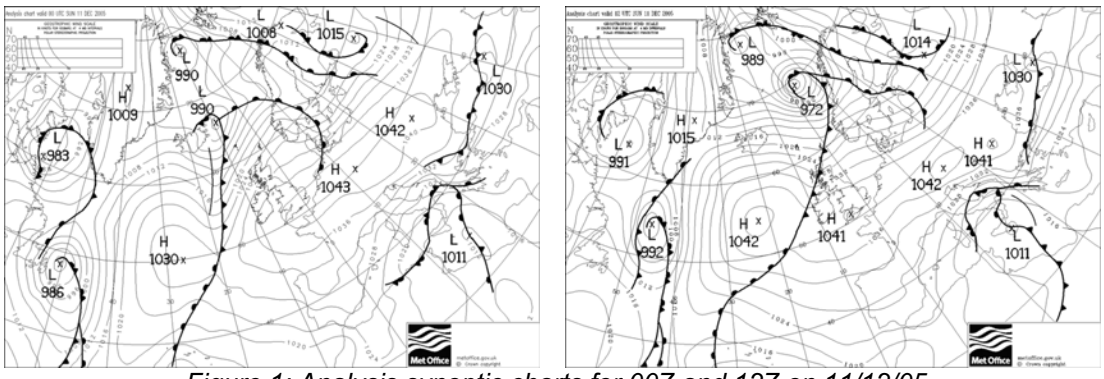


Figure 1: Analysis synoptic charts for 00Z and 12Z on 11/12/05

The plume, due to its high buoyancy, rose vertically upwards transporting most of the plume material well clear of the boundary layer. The resulting plume was captured on satellite imagery (see Figure 2) and had a fan like appearance caused by the significant wind shear. Two separate plumes were

observed at 14Z on Sunday, which joined up over London. This suggests that material was being transported to different levels within the atmosphere; the lower level material travelling south-eastwards whilst the upper level material travelling south-westwards. Comparing output from the Met Office's atmospheric dispersion model, NAME, with satellite imagery suggested that the plume was reaching a height of about 3000 m on Sunday 11th December. This was supported by a call received from Southampton Air Traffic Control shortly after 10am with a report from a commercial airline which indicated that the smoke plume was rising to a height of 9000 ft (2743 m) within the atmosphere.

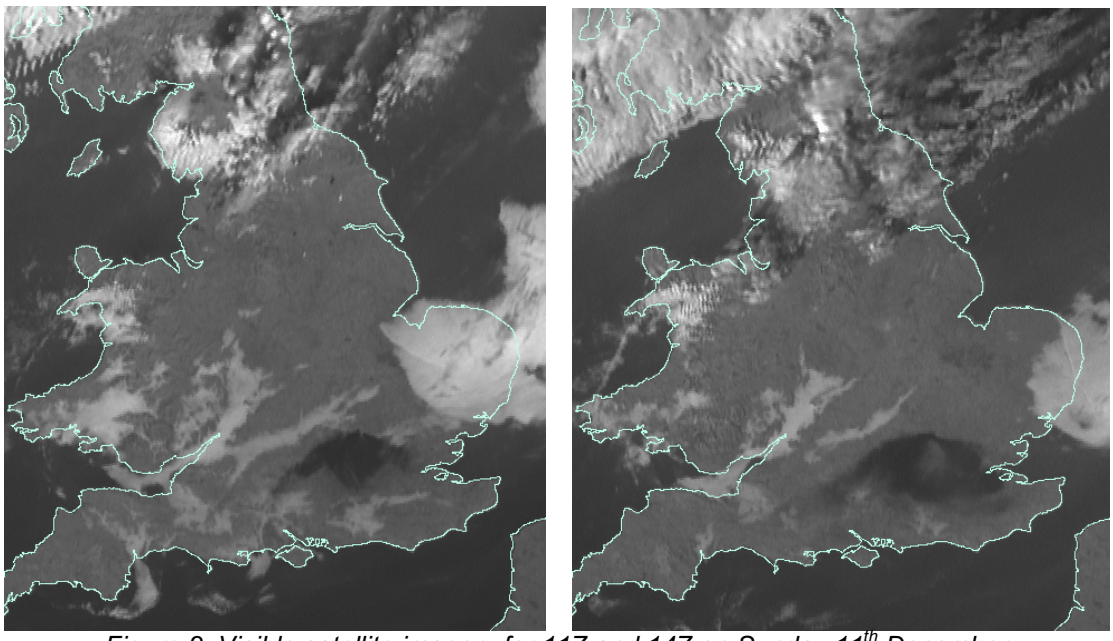


Figure 2: Visible satellite imagery for 11Z and 14Z on Sunday 11th December

2.2 Monday 12th December, 2005

High pressure was still dominating the UK weather resulting in a continuing stable atmosphere (see Figure 3). A weak front passed through on the Monday morning. Following the clearance of the front, winds were now from the north-east at all levels and resulted in a narrow plume being transported south-westwards across the Thames Valley area towards Southampton and Weymouth. The plume was detected at a height of approximately 2000 m above Bournemouth by the FAAM aircraft. It was again clearly visible on satellite imagery (see Figure 4). Fire fighting activities were scheduled to begin at 07Z and were expected to reduce the buoyancy of the plume. Observations made by eyewitnesses in the area suggested that the plume remained aloft.

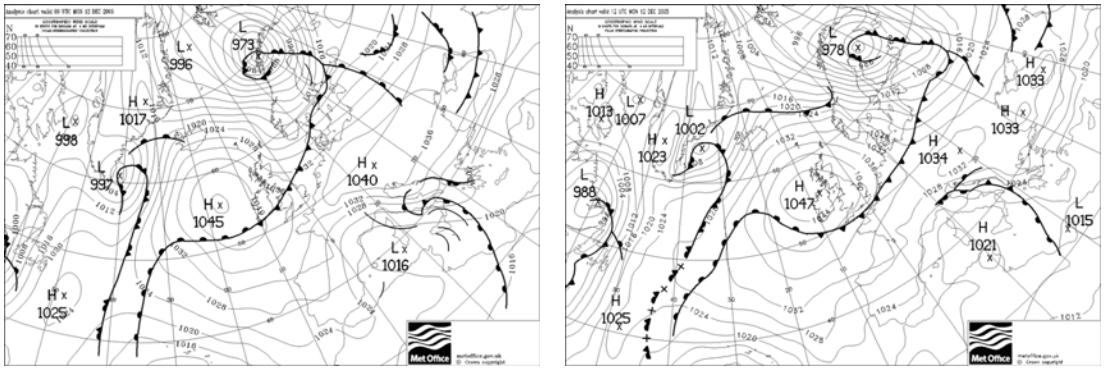


Figure 3: Analysis synoptic charts for 00Z and 12Z on 12/12/05

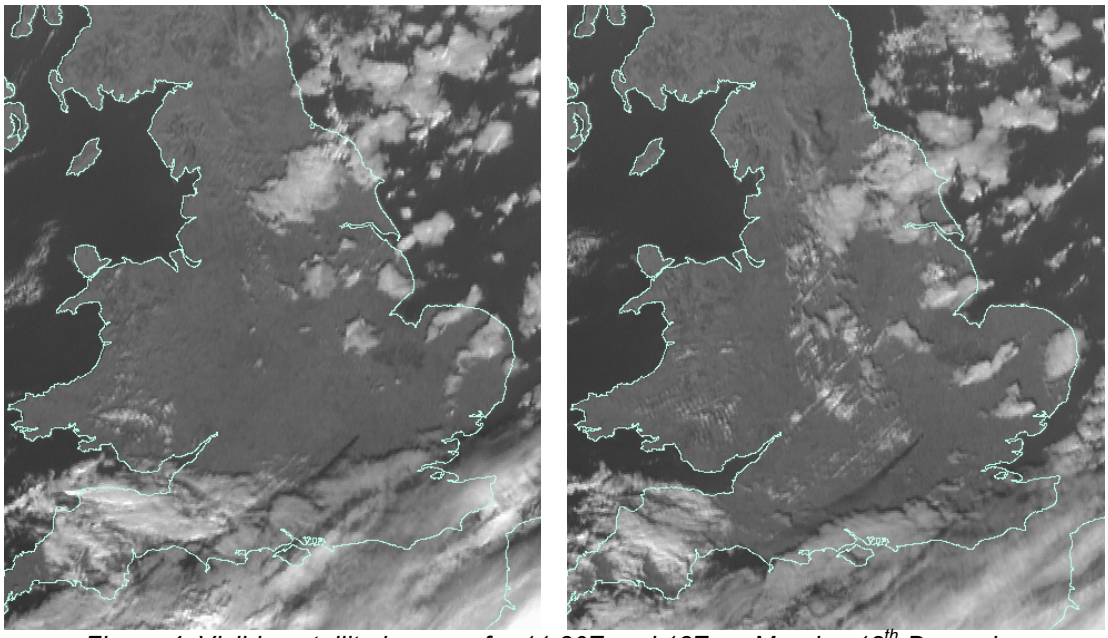


Figure 4: Visible satellite imagery for 11:30Z and 13Z on Monday 12th December

2.3 Tuesday 13th December, 2005

High pressure continued to dominate southern England maintaining a stable atmosphere (see Figure 5). Winds were from a north to north-easterly direction. As of Tuesday evening the plume was on a course taking it south of Heathrow airport. It was observed by the FAAM aircraft and was reported to be roughly 11 miles wide with a maximum height of 5000 ft (1524 m).

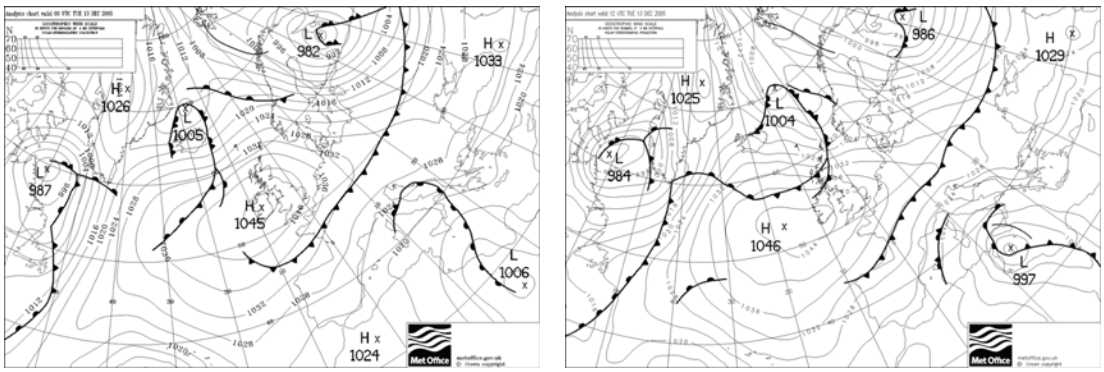


Figure 5: Analysis synoptic charts for 00Z and 12Z on 13/12/05

2.4 Wednesday 14th December, 2005

Winds were from a northerly direction, high pressure was still influencing the UK (see Figure 6) and the plume was still elevated. As the fire continued to be extinguished, there were concerns that the plume was likely to be detected at lower / ground levels due to a reduction in the buoyancy of the plume and increased atmospheric mixing due to a predicted increase in wind speed.

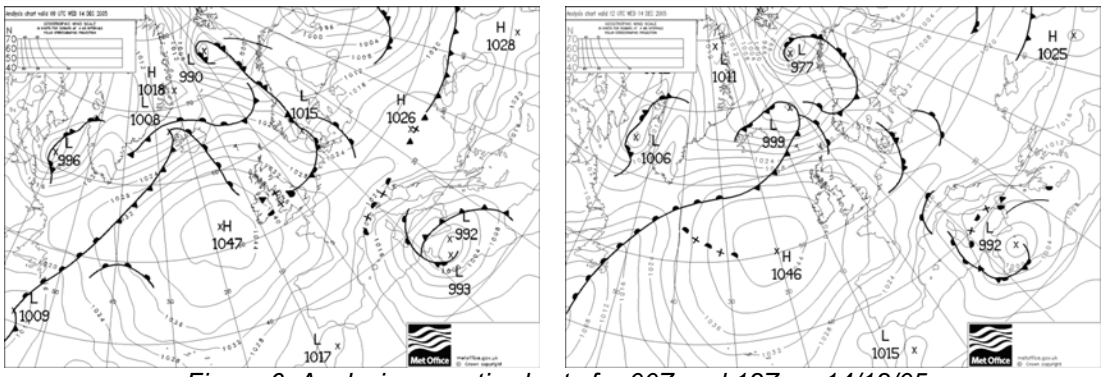


Figure 6: Analysis synoptic charts for 00Z and 12Z on 14/12/05

2.5 Thursday 15th December, 2005

By Thursday morning only a small fire remained at the Buncefield oil plant. Winds were now moderate (near surface wind speeds of approximately 4 – 5 m s^{-1}) and from a north-westerly direction. Thursday was a cloudy day with a cloud base of around 1700 to 1900 ft (518 to 579 m) and a neutral boundary layer. The remains of the plume were transported to the south-east and rapidly dispersed by a moderate wind.

3 Modelling of the plume

3.1 CHEMET

During the Buncefield fire, CHEMETs were issued by EMARC on a regular basis to the fire service and other departments requiring information. The CHEMET product consists of two parts: a map showing the predicted area at risk based on near surface meteorological observations or estimates of the wind speed, wind direction and atmospheric stability, and a textual forecast reporting on the meteorology and the likely effect of forecast weather conditions on plume behaviour. Figure 7 shows the area at risk map issued at 11:44Z on Sunday 11th December 2005 predicting a broad area at risk to the east and south of the oil depot with the area at highest risk to the south-east. The area at risk map does not account for the significant amount of wind shear present on this day and so does not capture the transport of the plume at higher levels south-westwards. In addition, the area at risk map does not account for the significant rise of the buoyant plume and gives no indication as to whether the plume remained aloft or was present at ground level.

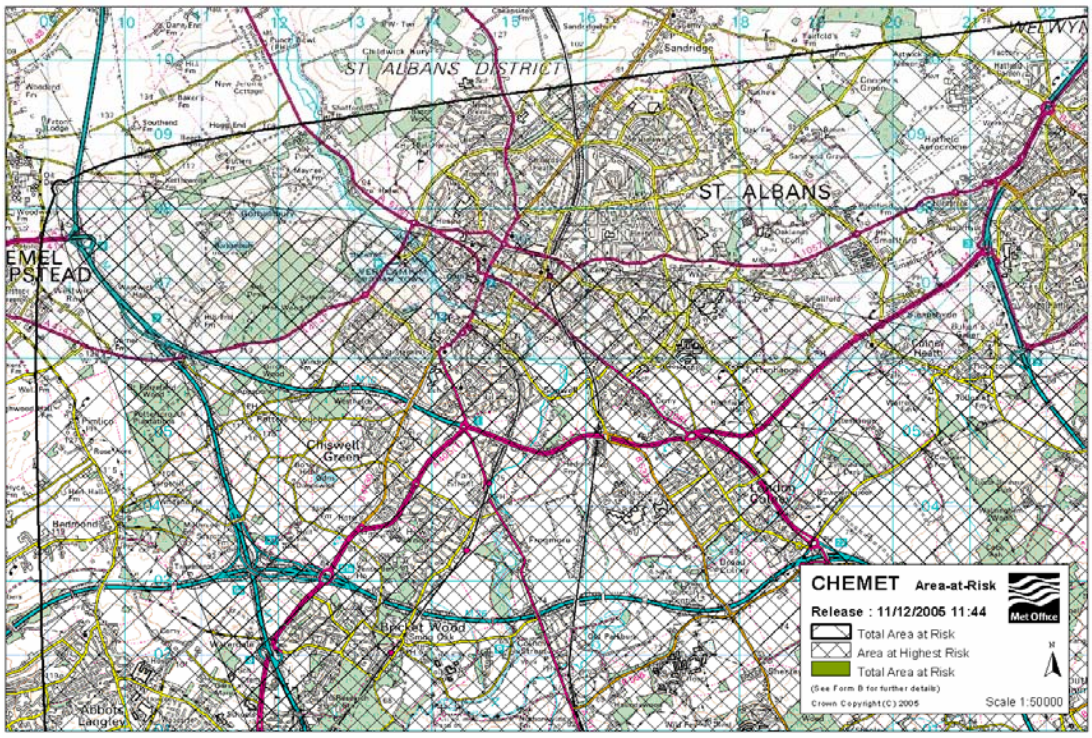


Figure 7: CHEMET issued at 11:44Z on 11/12/05

Figure 8 shows the area at risk map issued at 12:50Z on Monday 12th December 2005. This predicts a narrower area at risk to the south-west of the oil depot. On Monday 12th December 2005, winds were north-easterlies at all levels and there is good agreement between the CHEMET “area at risk” and the satellite imagery (see Figure 4).

During the incident, regular updates of CHEMET products were sent to gold control. In the latter stages, as the fire was being extinguished, three-hourly CHEMET forecasts updated every hour were sent from late morning on Tuesday 13th December 2005 until the early hours of Wednesday 14th December 2005 when updates were reduced to every three hours until the fire was extinguished

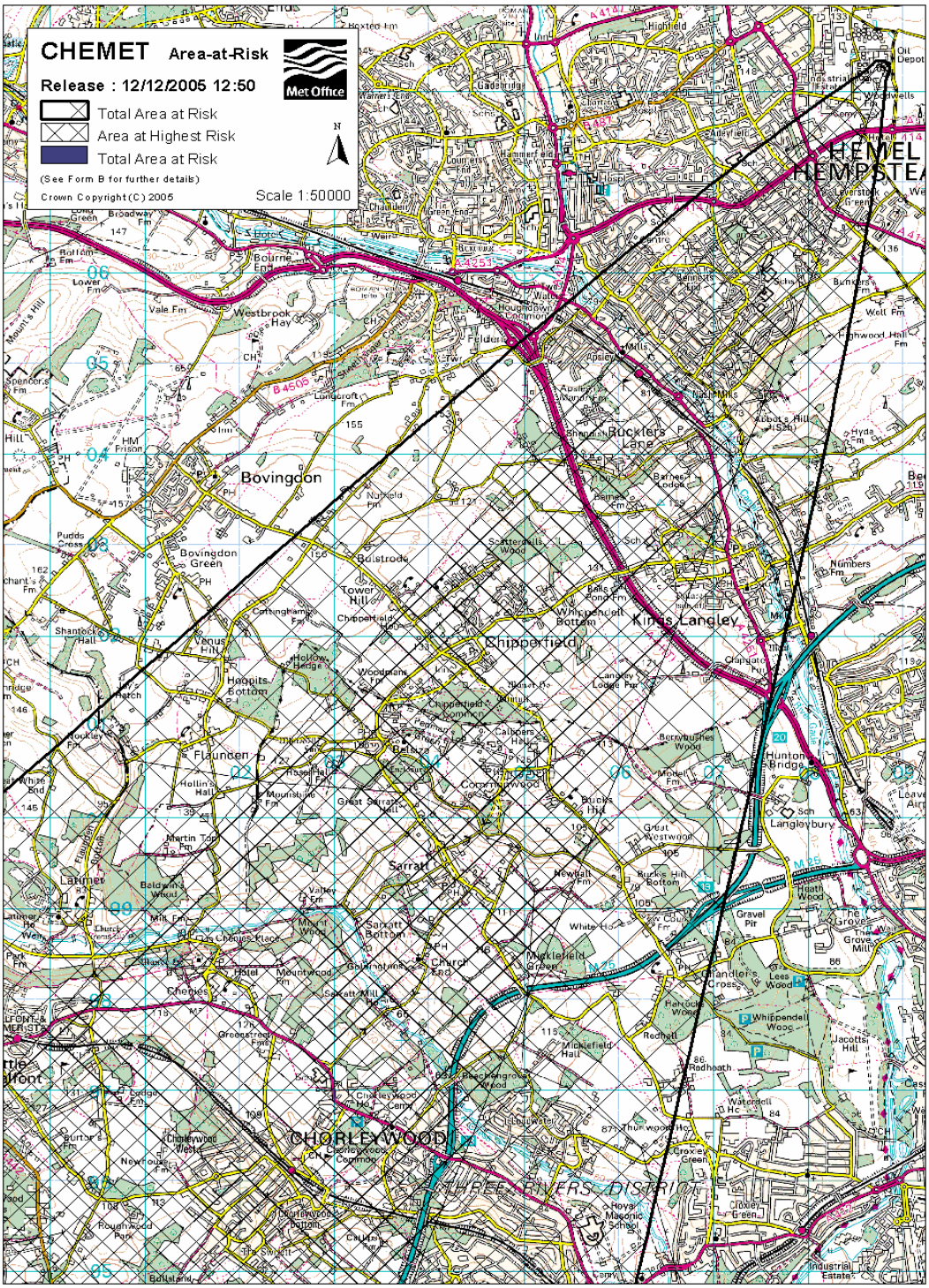


Figure 8: CHEMET issued at 12:50Z on 12/12/05

3.2 NAME

The Met Office's atmospheric dispersion model NAME (Numerical Atmospheric dispersion Modelling Environment) is a Lagrangian model in which a large number of 'particles' are released into the model atmosphere [7]. Each model particle represents a certain mass of the pollutant released and is advected by the mean three-dimensional wind with turbulent dispersion simulated by random walk techniques. In this study, NAME was used to

predict the transport and spread of the smoke plume from the Buncefield fire using three dimensional meteorological data from the Met Office's numerical weather prediction model (the Unified Model). The mesoscale version of the Unified Model was used which covers an area of the UK and north-west Europe with a horizontal resolution of approximately 12 km.

The precise nature of the release was initially unknown and there is still some uncertainty associated with the source details (e.g. emission rate, species, emission temperature, heat flux etc.). Observations and satellite images of the plume's location were used to assess the vertical height of the plume and to validate model results. Observations suggested that the plume reached a height of 3000 m during Sunday 11th December, 2005. Assumptions were made that the plume reached a lower height of 2000 m on Monday 12th December due to fire fighting activities. Initially a unit release of a tracer was modelled since the emission rate was unknown. The tracer was uniformly released over a vertical height of 200 – 3000 m during the first 24 hours of the fire and then reduced to 200 – 2000 m over the subsequent 24 hours. The initial rise of the buoyant plume due to the heat of the fire was therefore included as part of the release. Figure 9 shows the hourly averaged predicted plume over a height of 0 – 4000 m at 14Z on Sunday 11th December 2005 and at 13Z on Monday 12th December 2005. Since an arbitrary unit release is modelled, the predicted concentrations are not representative of actual concentrations within the plume. The NAME model predictions are useful, however, in predicting the transport and geographical spread of the plume. The higher concentrations within the plume will be indicative of actual areas where concentrations are highest, if a continuous constant emission rate released uniformly over the vertical height range discussed above is an appropriate assumption. In addition, if this is the case, results can easily be scaled by the estimated emission release rate to give predictions of concentrations within the plume.

Comparing the NAME predicted plume in Figure 9 with the relevant visible satellite imagery shown in Figures 2 and 4, we see that there is good agreement between the observed and predicted geographical extent of the plume on both Sunday 11th and Monday 12th December 2005.

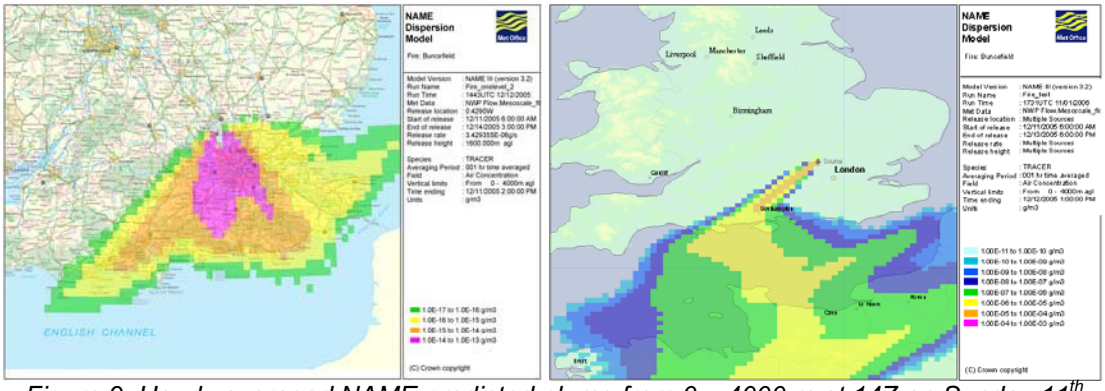


Figure 9: Hourly averaged NAME predicted plume from 0 – 4000 m at 14Z on Sunday 11th December 2005 and at 13Z on Monday 12th December 2005

Horizontal slices through the hourly averaged NAME predicted plume at 14Z on Sunday 11th December 2005 are shown in Figure 10 and are consistent with large quantities of wind shear. The NAME predicted plume between 0 and 500 m is transported in a south-easterly direction, the predicted plume between 500 and 1500 m is transported in a southerly direction and the predicted plume between 1500 and 3000 m is transported in a south-westerly direction. Using the satellite imagery for this time for comparison (see Figure 2), we therefore conclude that the plume from the fire reached a range of heights within the atmosphere. The plots in Figure 10 are noisier than those in Figure 9 since we have taken narrower horizontal slices which contain fewer model particles.

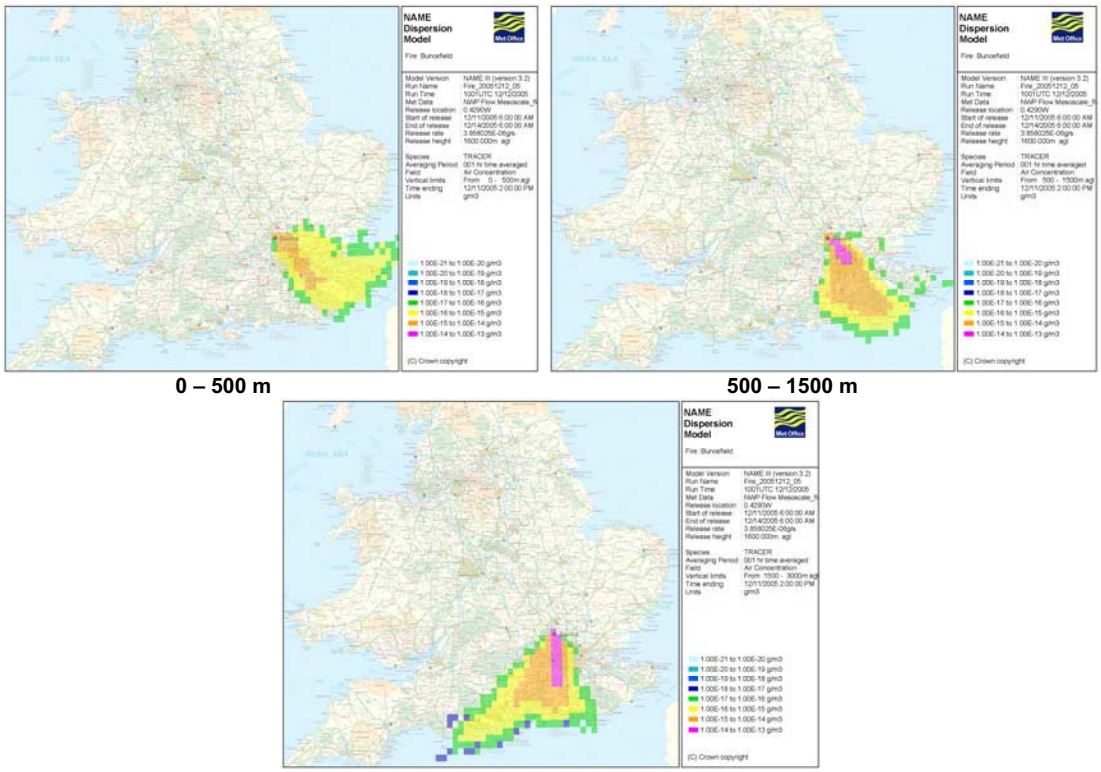


Figure 10: NAME predicted plume between 0 – 500m, 500 – 1500m and 1500 – 3000 m at 14Z on Sunday 11th December 2005

Further NAME modelling studies incorporated emission estimates and modelled the initial rise of the buoyant plume using the plume rise scheme.

4 Emission estimates

Calculations of emission estimates were obtained from fuel quantity estimates together with measurements of the plume taken using the FAAM aircraft.

A $PM_{2.5}$ emission rate was estimated using measurements (wind speed, plume dimensions (width and height) and $PM_{2.5}$ concentrations) from the FAAM aircraft on Tuesday 13th December, 2005 to be approximately 15 – 29 t hr^{-1} (4 – 8 kg s^{-1}). For comparison, national UK emission estimates are

approximately 17 t hr^{-1} for PM_{10} (EMEP[1]) and 6 t hr^{-1} for black carbon [2]. European emission estimates of black carbon are approximately 57 t hr^{-1} [2].

There is little information on emission factors from accidental burning of refined fuel. Some research was conducted, however, on the Kuwait oil fires in the early 1990s and information is available from earlier work on oil-spill clean-up trials. There is some doubt over the applicability of factors derived from oil fires (crude oil) to the burning of refined fuels. Other available emission factor scenarios from EMEP/Corinair and the NAEI database are based on controlled small scale combustion. These scenarios will not represent the correct mix of fuel and air in accidental burning situations and hence are likely to overestimate NO_x emissions whilst underestimating other emissions such as CO and particulate matter.

A number of emission scenarios based on different emission factors have been considered by Netcen. The open burning emission factors are thought to be most appropriate and are based on a US EPA review of literature in 2002/3 and published in 2004 [8]. The UK Petroleum Industry Association (UKPIA) inventory reported that there were 63.4 million litres (~50 kt) of fuel at the site. It has been suggested that about 75% of on-site fuel was burnt [11]. Table 1 shows an estimate of emissions calculated using the suggested open burning factors [4,8], UKPIA estimates of fuel quantities and assuming that 75% of on-site fuel was burnt. Total UK emission estimates from 2003 are shown for comparison. SO_2 levels were expected to be low since the fuels had very low sulphur content. A pseudo $PM_{2.5}$ value is calculated from the PM_{10} value and is based on data from a crude oil spill test fire in which 60% of total PM was found to be $PM_{3.5}$ [12]. Using this fractional value, which is based on the $PM_{3.5}$ fraction of total PM, for estimating $PM_{2.5}$ will result in an overestimate of the $PM_{2.5}$ fraction. However, given the uncertainty in the estimated emissions, the overestimate is not expected to be significant.

Pollutant	Open burning estimate	Total UK emissions (2003)[2]
NO_2	24.28 t	1570 kt
PM_{10}	5386.0 t	141 kt
$PM_{2.5}$	3231.6 t	86.9 kt
Dioxins	0.86 g I-TEQ	259 g I-TEQ
B[a]P	186.4 kg	4034 kg
CO	1118.2 t	2768 kt
NMVOC	66.0 t	1089 kt
Benzene	38.1 t	13.6 kt

Table 1: Open burning estimates of emissions from the Buncefield oil depot incident using UKPIA estimates of on-site fuel and assuming 75% of fuel burnt, together with total UK emissions from 2003 for comparison. (**I-TEQ** International Toxicity Equivalents)

Total also provided estimates of the amount of fuel on-site and these figures are thought to be more reliable than the UKPIA figures. Their best estimate of the likely fuel on site is 105 million litres resulting in a worst case scenario of approximately 25 kt of CO_2 emissions. This figure assumes 100% combustion of carbon which is likely to be an overestimate since a significant amount of

[1] http://webdab.emep.int
[2] http://www.naei.org.uk

carbon will have been emitted as soot and particulate matter. The worst case scenario for other pollutant emissions, using Total's estimate of fuel on site and open burning emission factors [4,8], is shown in Table 2.

Pollutant	Open burning estimate	Total UK emissions (2003)
NO_2	54.6 t	1570 kt
PM_{10}	12109.6 t	141 kt
$PM_{2.5}$	7265.7 t	86.9 kt
Dioxins	1.93 g I-TEQ	259 g I-TEQ
B[a]P	419 kg	4034 kg
CO	2514.1 t	2768 kt
NMVOC	148.3 t	1089 kt
Benzene	85.6 t	13.6 kt

Table 2: Open burning estimates of emissions from the Buncefield oil depot incident using Total's estimate of on-site fuel and assuming 100% of fuel burnt, together with total UK emissions for 2003 for comparison. (**I-TEQ** International Toxicity Equivalents)

In response to the fire fighting efforts, it has been suggested that the following scaling factors are used for the relative size of emissions on different days during the event; 1 for Sunday, 0.9 for Monday, 0.4 for Tuesday and 0.2 for Wednesday (private communication, Noel Nelson, Defra). These are applied below as relative scalings, keeping the total emissions over the duration of the fire fixed. It is hoped that more detailed information on the extinguishing of fuel tanks can be obtained from the Hertfordshire fire brigade and used to give more realistic time varying emission estimates.

5 Incorporating emission estimates into the plume modelling

NAME was rerun using the emission scenario described above which enabled concentrations within the plume to be predicted for the worst case scenario (100% of 105 million litres of fuel burnt). The release height was refined from the initial modelling exercises to reflect additional information obtained from observations. A release height from 500 m to 3000 m was chosen for the first 24 hour period. The upper release height was based, as before, on comparisons of model predictions with satellite imagery, possible due to the significant wind shear present on Sunday 11th December, together with a single report from a commercial airline. The lower release height was based on observations from the FAAM aircraft (described in Section 6.1) which detected the plume at a height of 500 m above ground on Tuesday 13th December both near to the source and at a distance of approximately 78 km downwind. Following the first 24 hour period, the upper release height was reduced to 2000 m taking into account the likely effects of fire fighting activities. This is roughly in line with observations from the FAAM aircraft which detected the plume at a height of 2000 m on Monday 12th December and at a height of 1470 m but not at a height of 1750 m on Tuesday 13th December.

Figure 11 shows the NAME predicted hourly averaged plume between 0 and 4000 m at 14Z on Sunday 11th December and at 13Z on Monday 12th December using the emission estimates and release scenario described above. Comparing Figure 11 with the corresponding satellite imagery in

Figures 2 and 4 shows a good representation of the smoke plume by NAME. Figure 12 shows predicted hourly averaged PM_{10} boundary layer concentrations at 12 hourly intervals. The smoke plume is predicted to have been transported over an area heading roughly south-eastwards from the oil depot through to south-westwards. Boundary layer concentrations are predicted to be low on Sunday 11th December with most of the plume present aloft with minimal mixing down to ground. By Monday 12th December, the Unified Model predicts that the boundary layer was deeper and consequently predicted boundary layer concentrations were higher as the lower part of the plume was entrained into the boundary layer. Boundary layer concentrations are clearly very sensitive to the lower release height of which there is significant uncertainty. This, coupled with the uncertainty in the total emissions and the rate of the emission, results in low confidence in actual predicted concentrations. Nonetheless, the NAME results are useful in predicting the transport and geographical spread of the plume and in giving some guidance on the worst case scenario possible.

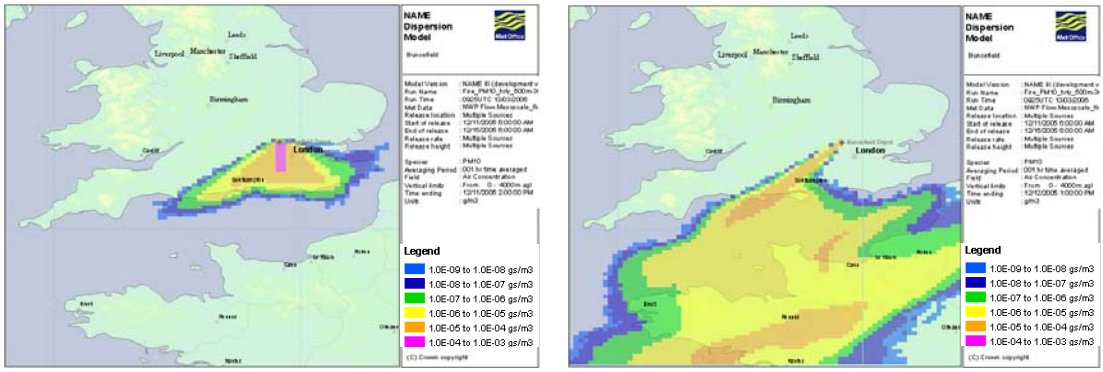


Figure 11: NAME predicted hourly averaged PM_{10} concentrations between 0 and 4000 m at 14Z on Sunday 11th December and 13Z on Monday 12th December

The maximum hourly averaged PM_{10} boundary layer concentration predicted for this worst case scenario by NAME is 151 μg m^{-3} averaged over a 7 km by 8.4 km region and occurred at 04Z on Wednesday 14th December near to the source.

6 Plume measurements and observations

Measurements and observations of the plume came in from a number of different sources encompassing both routine air quality measurements and measurements made specifically during the Buncefield incident. Local monitoring in and around the depot during the incident was undertaken by Netcen, by the fire brigade's scientific advisors (Bureau Veritas) and by the Health and Safety Laboratories. Automatic monitoring of national air quality is provided routinely by Netcen and is monitored by Defra. Regional air quality information is also available from local monitoring networks. During the incident, Defra and the Environment Agency were involved in monitoring air quality on the ground throughout London. In addition, aircraft measurements by the FAAM aircraft (a converted BAe146-301 jointly funded by the Met Office and NERC) were taken from within the plume on Monday 12th and Tuesday 13th December.

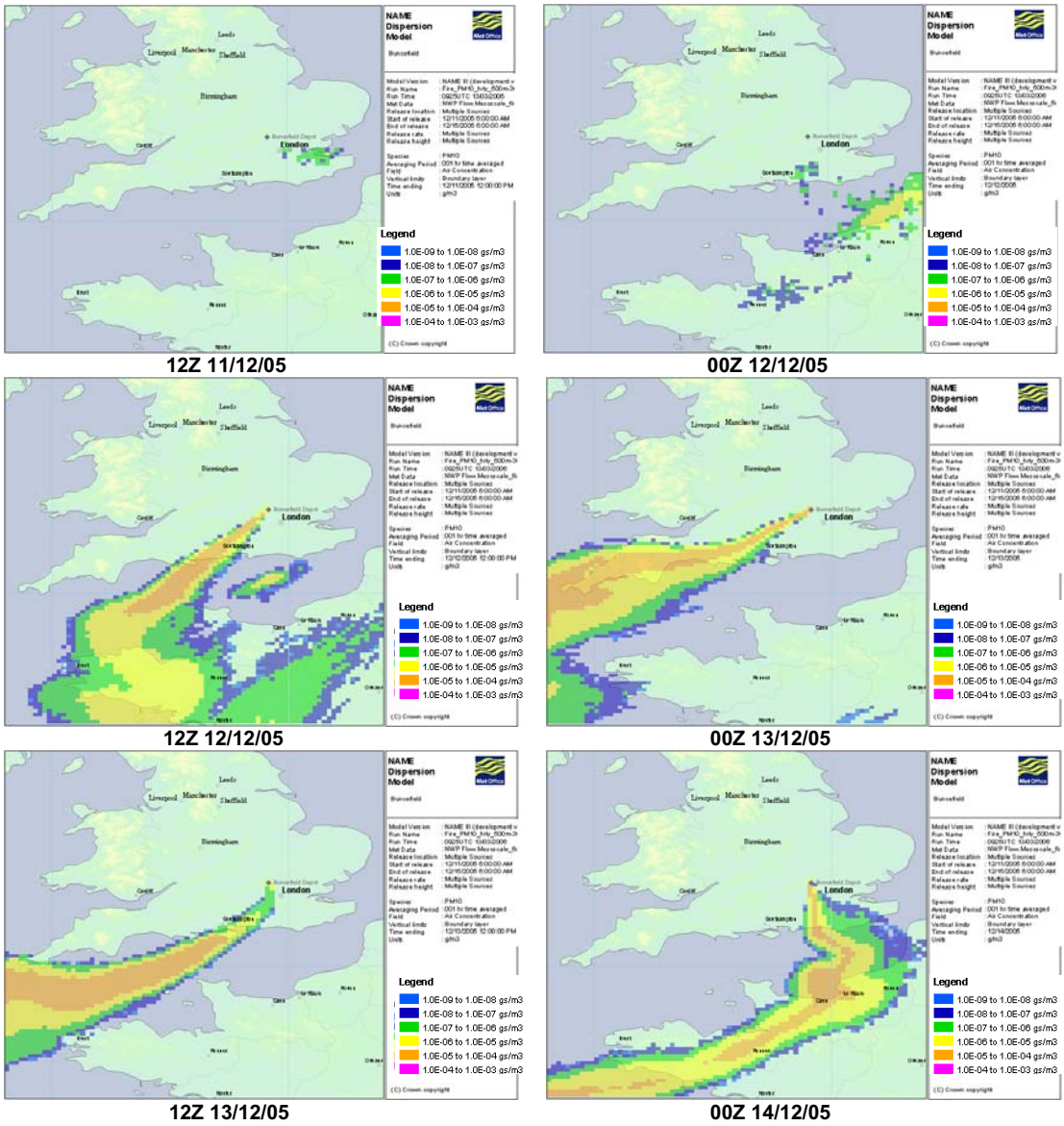


Figure 12: NAME predicted hourly averaged PM_{10} boundary layer concentrations from 12Z on Sunday 11th December until 00Z on Wednesday 14th December at twelve hourly intervals assuming 100% of 105 million litres burnt

6.1 Aircraft measurements

The FAAM aircraft has an airspeed of 120 m s^{-1} and is equipped with a suite of instrumentation to obtain measurements of atmospheric gases and aerosols. The Aerosol Mass Spectrometer (AMS) measures the size segregated chemical composition of volatile and semi-volatile particles (i.e. not black carbon) in the 50 to 500 nm diameter range. The Particle Soot Absorption Photometer (PSAP) has a sampling rate of 30 seconds and measures the bulk absorption coefficient of aerosol particles, from which the mass concentration can be inferred. The PSAP instrument does not capture all PM_{10} and has an upper limit of about 3 – 4 μm. In addition, particle sizes cannot be segregated with the PSAP. The Passive Cavity Aerosol Spectrometer probe (PCASP) measures the number of particles in the range 0.1 to 3 μm in diameter and their size distribution using laser scattering of air

samples. It has a sampling rate of 1 Hz. Estimates of mass concentrations can be obtained from the PCASP measurements using the equation

$$c = \frac{4}{3}\pi \sum_j \left(N_j r_j^3 \right) \rho , \quad (1)$$

where c is the concentration, N_j is the number of particles in size bin j, r_j is the radius of particles in size bin j and ρ is the particle density. This estimation requires knowledge of the refractive index of the particles, to calibrate the size bins, and of the particle density. Measurements of O_3, CO, SO_2 and NO_x were also taken from the aircraft. O_3 and CO data were sampled at a rate of 1 Hz, whilst the SO_2 and NO_x data are integrated over a 20 second time period. A Cloud Particle Image profiler (CPI) was also available and was used to study particles larger than 5 μm diameter. Air filter samples were obtained using quartz filters and subsequently analysed for levels of poly aromatic hydrocarbons (PAHs), dioxins, furans and PCBs by the Health and Safety Laboratories (HSL), Buxton and by Harwell Scientifics.

The FAAM research flight on the afternoon of Monday 12th December 2005 detected elevated aerosol levels at a height of 2000m above Bournemouth. More extensive measurements within the plume were conducted on Tuesday 13th December 2005 (flight identifier B149). This flight took place between 11:59Z and 16:10Z and included runs in and above the plume both at a distance of around 78 km from the source and directly over the Buncefield site. Figure 13 shows the flight path undertaken by the aircraft and details of the runs both in and above the plume are given in Table 3. Measurements taken from within the plume are presented in more detail in Appendix B. The plume was initially detected at 13:23Z on Tuesday 13th December 2005 at 51.06N 0.62W at a distance of approximately 78 km due south of Buncefield. At this distance downwind, penetrations of the plume were made by the aircraft at altitudes between 2000 and 5000 ft (610 to 1524 m). The plume was narrow with a width of approximately 11 km. Wind measurements within the plume at a height of 4000 ft (1219 m) were 15 – 20 knots (7.7 – 10.3 m s^{-1}) at a bearing of 020 degrees. PCASP measurements gave background aerosol readings of between 50 and 300 particles cm^{-3} rising to 3600 particles cm^{-3} within the plume at 78 km downwind of the source. Over the source region the peak in-plume particle concentration measured with the PCASP was 22,400 cm^{-3} at 15:55Z and at a height of 1700 ft (518 m). This corresponded to both the peak CO measurement of 501 ppb (which is not significantly high - indeed CO measurements were just as high near the ground) and with the maximum 30 second averaged total black carbon mass concentration of 100 μg m^{-3} inferred from the PSAP measurements. The filter analysis showed that levels of hydrocarbons within the plume were very low, for example, levels of benzene were below those typically measured near busy roads. Furthermore, the AMS measurements gave no evidence of any poly aromatic hydrocarbons (PAHs) or significant amounts of organic particles at any time in the flight which suggests that the main constituent of the plume was black carbon (or soot). Most particles were below 0.5 - 1 μm in diameter with the largest particles misshapen soot conglomerates of about 100 μm in size. Using a range of values of refractive index and density for black carbon [5], the mean concentration of $PM_{2.5}$ calculated using Equation (1) from the PCASP measurement taken during run 14, which was over the source in an along

plume direction, was 461 μg m^{-3} with an uncertainty ranging from 290 – 572 μg m^{-3}. Assuming, as before, that $PM_{2.5}$ is 60% of the mass of PM_{10}, the estimated $PM_{2.5}$ concentration gives an estimated mean PM_{10} concentration near the source of 768 μg m^{-3} with an uncertainty ranging from 483 – 953 μg m^{-3}. The difference in the values derived from the PSAP and PCASP highlights the uncertainty in determining the mass concentration of the aerosol within the plume from the aircraft data.

Estimates for the $PM_{2.5}$ mass flux, calculated from the runs approximately 78 km downwind of the source, were made by integrating the PCASP mass concentration cross-plume profile multiplied by the plume depth and the horizontal wind speed and resulted in values ranging from 4.0 – 7.9 kg s^{-1} depending on the assumptions of refractive index and density of the black carbon. This gives an estimated emission rate for PM_{10} of 6.7 – 13.2 kg s^{-1}, assuming that $PM_{2.5}$ comprises 60% of the mass of PM_{10} and that there are no losses or gains in the mass of aerosol in the plume from the source region to 78 km downwind. The PM_{10} emission rate value calculated from the aircraft data is smaller than that calculated from the emission estimates in Table 2 (assuming that 100% of 105 million litres of fuel on site was burnt) and the suggested daily scaling factor for Tuesday 13th December described in Section 4, namely 22.4 kg s^{-1}. This suggests that NAME predictions of PM_{10} concentrations presented as a worst case scenario in Section 5 will be an overestimate. However, one should bear in mind that there is considerable uncertainty in both emission rate estimates.

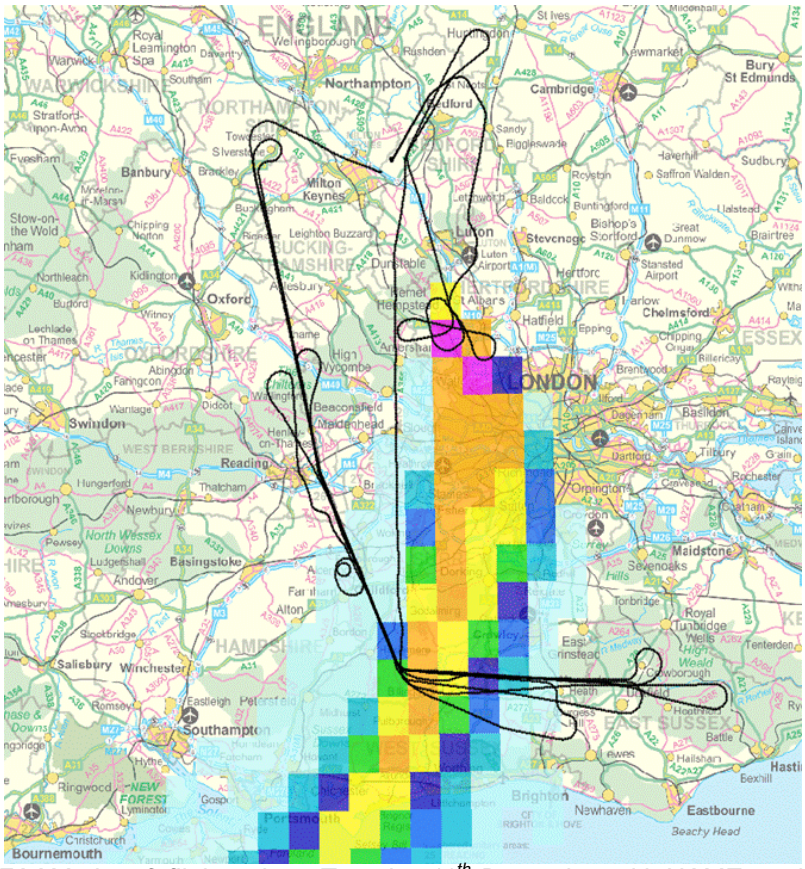


Figure 13: FAAM aircraft flightpath on Tuesday 13th December with NAME predicted plume

Run	Time (Z)	Height	Peak measurements	Comments
1	12:08:39 – 12:29:25	8900 ft (2713 m)	O_3: 53 ppb CO: 123 ppb NO_X: 0.5 ppb PCASP: 343 cm^{-3} SO2: 0.83 ppb	Above plume downwind of source
2	12:32:40 – 13:04:02	5700 ft (1737 m)	O_3:53 ppb CO: 125 ppb NOx: 0 ppb* PCASP: 389 cm^{-3} SO2: 0.73 ppb	Above plume downwind of source
3	13:07:29 – 13:28:26	4700 ft (1433 m)	O_3: 55 ppb CO: 137 ppb NOx: 0 ppb* PCASP: 3014 cm^{-3} SO2: 0.83 ppb	In plume downwind of source
4	13:31:25 – 13:49:07	3800 ft (1158 m)	O_3: 50 ppb CO: 293 ppb NO_x: 10.3 ppb PCASP: 2695 cm^{-3} SO2: 1.9 ppb	In plume downwind of source
5	13:51:32 – 14:12:44	2800 ft (853 m)	O_3: 43 ppb CO: 211 ppb NO_x: 10.8 ppb PCASP: 993 cm^{-3} SO_2: 5.2 ppb	In boundary layer downwind of source Urban pollution mixed with pollution from plume
6	14:17:02 – 14:35:52	1800 ft (549 m)	O_3: 39 ppb CO: 205 ppb NO_x: 11.6 ppb PCASP: 1448 cm^{-3} SO_2: 3.5 ppb	In boundary layer downwind from source Urban pollution and pollution from plume
7	14:39:50 – 14:56:28	3700 ft (1128 m)	O_3: 48 ppb CO: 192 ppb NO_x: 8.9 ppb PCASP: 3639 cm^{-3} SO_2: 2.3 ppb	In plume downwind of source Increase in organics (unburned hydrocarbons)
8	14:58:22 – 15:13:25	4300 ft (1311 m)	O_3: 52 ppb CO: 120 ppb NO_x: 1.1 ppb PCASP: 521 cm^{-3} SO_2: 0.83 ppb	Heading back closer to Hemel Hempstead
9	15:36:34 – 15:38:58	3600 ft (1097 m)	O_3: 51 ppb CO: 117 ppb NOx: 0 ppb* PCASP: 168 cm^{-3} SO_2: 0.83 ppb	In holding awaiting permission to fly closer to the source
10	15:39:30 – 15:41:32	3100 ft (945 m)	O_3: 43 ppb CO: 134 ppb NO_x: 0.8 ppb SO2: 1.1 ppb	Over top of source In Cloud
11	15:42:10 – 15:43:42	2500 ft (762 m)	O_3: 39 ppb CO: 142 ppb NO_x: 3.0 ppb SO2: 1.5 ppb	Cloud Base
12	15:43:48 – 15:46:40	2200 ft (671 m)	O_3: 38 ppb CO: 147 ppb NO_x: 2.6 ppb PCASP: 5188 cm^{-3} SO2: 1.5 ppb	In plume directly over source AMS suggests soot (unburned hydrocarbons)
13	15:48:15	1700 ft	O_3: 37 ppb	In plume directly over

	– 15:50:51	(518 m)	CO: 215 ppb NO_x: 4.3 ppb PCASP: 10170 cm^{-3} SO2: 2.7 ppb	source
14	15:53:47 – 15:55:17	1700 ft (518 m)	O_3: 37 ppb CO: 501 ppb NO_x: 4.4 ppb PCASP: 22369 cm^{-3} SO_2: 1.6 ppb	Along plume run directly over source CPI shows large particles of size 10 – 50 µm

*Table 3: Measurements from the aircraft runs in and above the Buncefield plume (flight identifier B149). * - not detectable above noise levels*

6.2 Ground level local monitoring undertaken during the incident

Netcen took measurements of PM_{10} and VOCs both on site and at other locations within Hemel Hempstead during the incident (see Figure 14). VOC measurements were taken on Monday 12th December at 18Z at location 2, situated five miles south-west of the fire on a hill where the plume appeared to be grounding. VOC concentrations at location 2 were found to be well below average concentrations measured at the urban site at Marylebone Road in London. On Tuesday 13th December, VOC measurements were made at 11:30Z, 11:40Z and 11:55Z at location 3, at 13:10Z at location 4, at 16:42Z at location 5 and at 16:55Z at location 6. On Thursday 14th December, VOC measurements were taken at 12:20Z, 13:25Z and 13:35Z at location 7. VOC measurements on-site were significantly higher than those measured away from the site. The VOC measurements made off site but within Hemel Hempstead were slightly higher than would be expected of an urban area.

On Monday 12th December 2005, Netcen monitored PM levels at locations 1 and 2. Location 1 was just outside of the exclusion zone (approximately 1 mile south-west of the fire). PM measurements were recorded over a 30 minute period at location 1 and over a 60 minute period at location 2. The measured PM_{10} levels were low except for a five minute period of increased pollution at location 1 and a short blip lasting for just one minute at location 2. On Tuesday 13th December, PM measurements were taken at locations 3, 4 and 6. Netcen reported that ground level PM_{10} measurements made on Tuesday 13th December were high near to the source (~200 m from the fire) particularly directly underneath the plume. Measurements taken later on that afternoon from location 6, a residential area within Hemel Hempstead where the plume appeared to be close to grounding, did not show any elevated concentrations of PM_{10}. Netcen concluded that the risk to air quality was restricted to an area local to the fire, by Wednesday 14th December 2005. On Thursday 14th December, PM concentrations were measured at location 7. Elevated levels were detected at this near source location.

Further details of the PM_{10} and VOC measurements taken by Netcen during the incident can be found in the 'Initial review of air quality aspects of the Buncefield oil depot explosion' report [11].

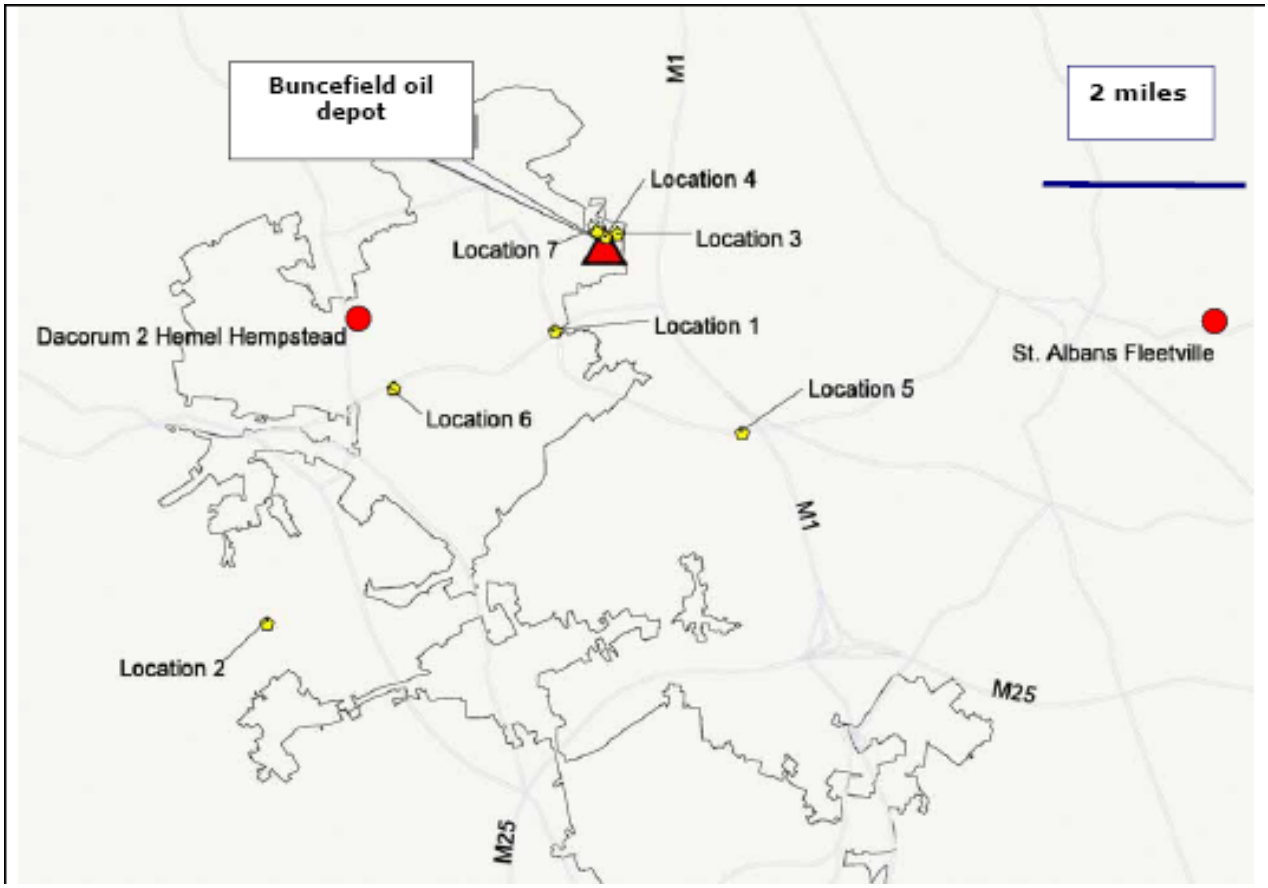


Figure 14: Locations of PM_{10} and VOC monitoring both on site and at other locations within Hemel Hempstead undertaken by Netcen during the period Tuesday 12th to Thursday 14th December 2005 (Netcen, 2006)

6.3 Routine observations

Netcen reported that the UK's Automatic Urban and Rural Network (AURN) did not show a significant increase in surface pollution levels related to the Buncefield oil fire plume. Measurement sites to the south of Hemel Hempstead chosen based on observations and predictions of the plume from Buncefield were identified and data from the sites analysed for peaks. 'Moderate' levels of PM_{10} were observed at some sites during the evening of Sunday 11th December, 2005. These were, however, often coincident with peaks in other pollutants, namely CO and NO_x which implies that they were consistent with periods of general high pollution potentially caused by traffic. In addition, pollutant levels do not appear to be significantly different to those recorded at other times. With high pressure dominating, pollutant levels were, in general, steadily increasing during the preceding week until a frontal system passed through in the early hours of Monday 12th December, 2005.

The Environmental Research Group (ERG) at King's College, London manage regional air quality monitoring networks in the south-east of the UK which have a larger number of monitoring sites over the area of interest. During the Buncefield incident, data collection frequencies from the regional networks were increased to provide measurements on an hourly basis. ERG suggested that grounding of the plume was detected at a number of sites in east Surrey and Sussex, North London and St Albans during the incident (see

Table 4). Fifteen minute averages of NO, NO_2, NO_X, PM_{10} and CO were measured and data from the 3rd - 15th December 2005 were analysed. Figure 15 shows the location of the ERG monitoring sites used for analysis. The locations shown in red are monitoring sites where King's Environmental Research Group (ERG) suggest the plume was detected. The locations shown in blue are non roadside sites from the same area and the locations shown in black are additional CO monitoring sites from the area. Figure 16 shows time series of 15 minute mean concentrations of PM_{10}, NO_X and, where available, CO for four sites where grounding of the plume may have been detected in the measurements: Horsham (HO2), Lewes (LS2), Dorking (MV3) and St Albans (SA1). In addition, 24 hourly rolling mean concentrations of PM_{10} are shown in green and the dashed horizontal lines denote the boundaries between 'low', 'moderate' and 'high' levels of PM_{10} (based on 24 hourly means). The red vertical line denotes the time of the explosion at Buncefield. Following the fire at Buncefield, air pollution levels at all the ERG measurement sites in Figure 15 were not unusually high. In fact, the highest pollution levels over the period studied occurred in the week preceding the fire. From the ERG monitoring sites analysis, the highest 15 minute mean concentrations of NO, NO_2 and NO_X over the period 3rd - 15th December 2005 were measured at Haringey Council Offices, High Road (A10) (HG1) with peak measurements of 540 ppb at 19:45Z on 9th December 2005, 110 ppb at 20:30Z on 9th December 2005 and 650 ppb at 19:45Z on 9th December 2005, respectively. The air pollution index[3] for NO_2 was classed as 'low' at all sites throughout. The highest 15 minute mean concentration of CO was measured at Salisbury (EN3) with a peak value of 9.36 ppm at 05:00Z on 10th December 2005. The air pollution index for CO was also classed as 'low' at all sites throughout. The highest 15 minute mean concentration of PM_{10} was measured at Neasden (BT5) with a peak measurement using the Tapered Element Oscillating Microbalance (TEOM) of 315 µg m^{-3} at 15:15Z on 5th December 2005. The air pollution index, based on 24 hourly running means, was classed as 'high' during this time. Following the fire, 'moderate' PM_{10} levels were detected at two monitoring sites; Horsham Roadside (HO2) and Lewes 2 Roadside (LS2) (see Figure 16). PM_{10} concentration levels at all other sites were classed as 'low' during the incident. A general increase in air pollution from 9th – 12th December 2005 is evident in the measurement data (see Figure 16). This is consistent with the dominance of a high pressure weather system over the south of the UK with light winds which allowed pollutants to accumulate. During the morning of the 12th December 2005 a weak front passed through bringing cleaner air to the region and an increase in winds. This is evident in the air quality measurements which show a sharp decrease in pollution levels.

A number of sites (for example, Horsham, Lewes, Dorking and St Albans shown in Figure 16) show a brief peak in 15-minute mean PM_{10} concentrations during the Sunday evening (11th December 2005) and the Monday morning (12th December 2005) which could be due to wide-scale grounding of the plume (see Table 4). However, in the majority of cases this

[3] http://www.airquality.co.uk/archive/standards.php#band

was accompanied with a brief peak in other pollutants (CO, NO_X etc.) and so could be indicative of general air pollution.

Incident	Date	Time of max concentration	Area	Site	Max 15 min mean conc µg m^{-3} (grav)[4]
A	11-Dec	16:15	Surrey & Sussex	Mole Valley 3 - Dorking	156
A	11-Dec	17:45	Surrey & Sussex	R'gate & Bans 1 - Horley	133
A	11-Dec	19:15	Surrey & Sussex	Lewes 2	217
A	11-Dec	22:45	Surrey & Sussex	Horsham 2	290
B	11-Dec	20:30	Hertfordshire	St Albans - Fleetville	133
C	11-Dec	18:30	North London	Haringey 2 - Priory Pk[5]	102
C	11-Dec	18:45	North London	Haringey 1 - Tottenham	122
C	11-Dec	19:15	North London	Islington 2 - Holloway Rd	137
C	12-Dec	02:30	North London	Brent 5 - Neasden	130
D	14-Dec	03:00	North London	Barnet 2	98
D	14-Dec	07:30	Hertfordshire	Watford	114

Table 4: Maximum 15 minute mean PM_{10} concentrations measured during the Buncefield incident and thought by ERG to be due to plume grounding (King's College London, 2006)

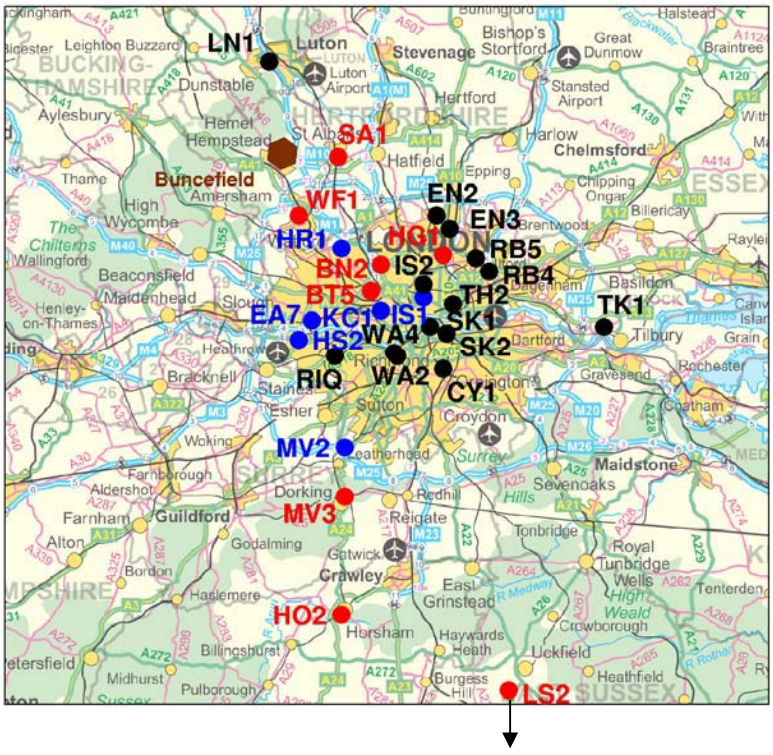
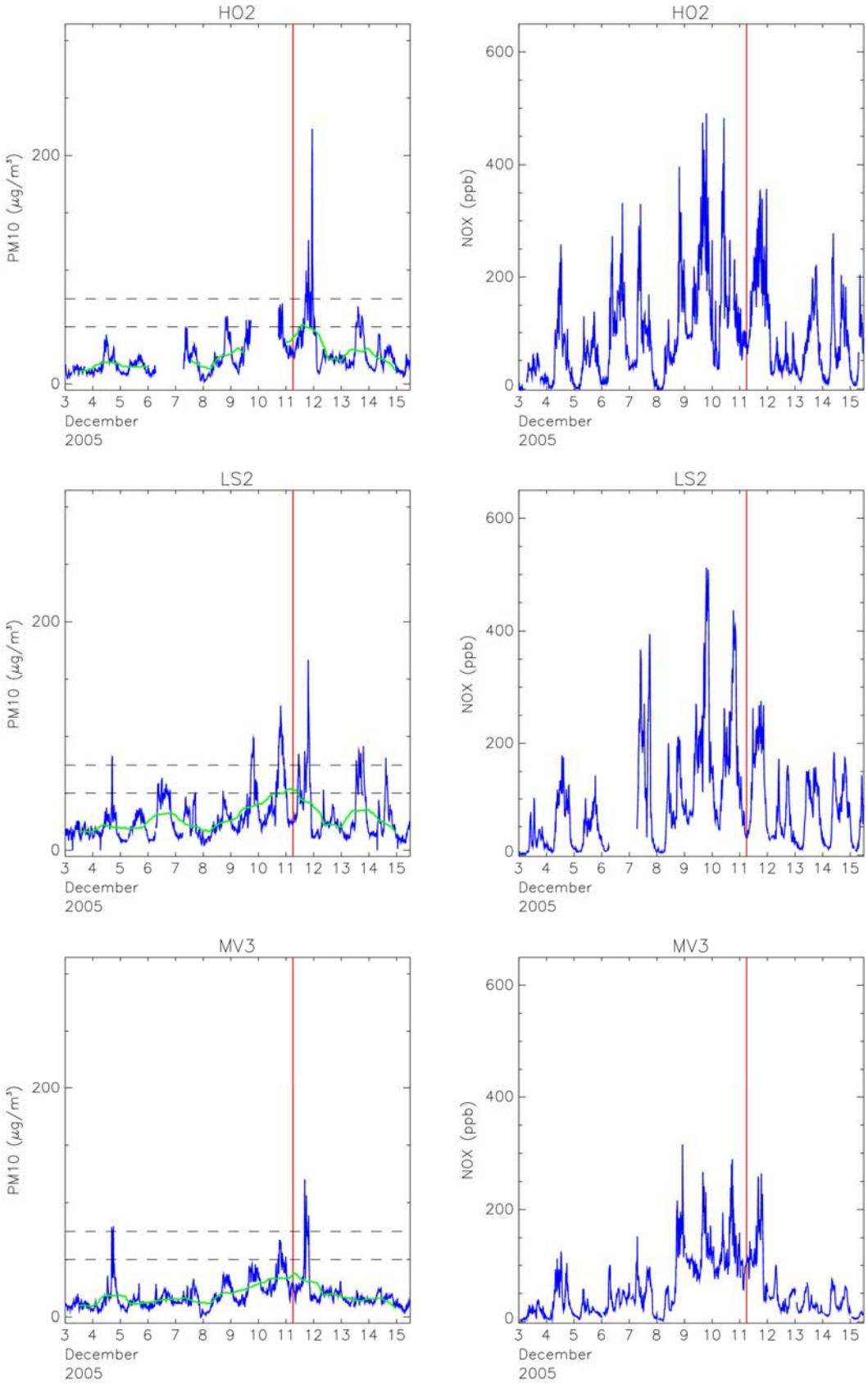


Figure 15: Location of the ERG monitoring sites studied. Sites at which ERG suggest the plume was detected are shown in red, non roadside sites are shown in blue and additional CO monitoring sites are shown in black

[4] Concentrations are expressed as gravimetric equivalent. A conversion factor of 1.3 is applied to TEOM measurements.
[5] Beta Attenuation Monitor (BAM) which has only hourly measurement resolution. To convert to gravimetric equivalent, a conversion factor of 0.81 is applied.



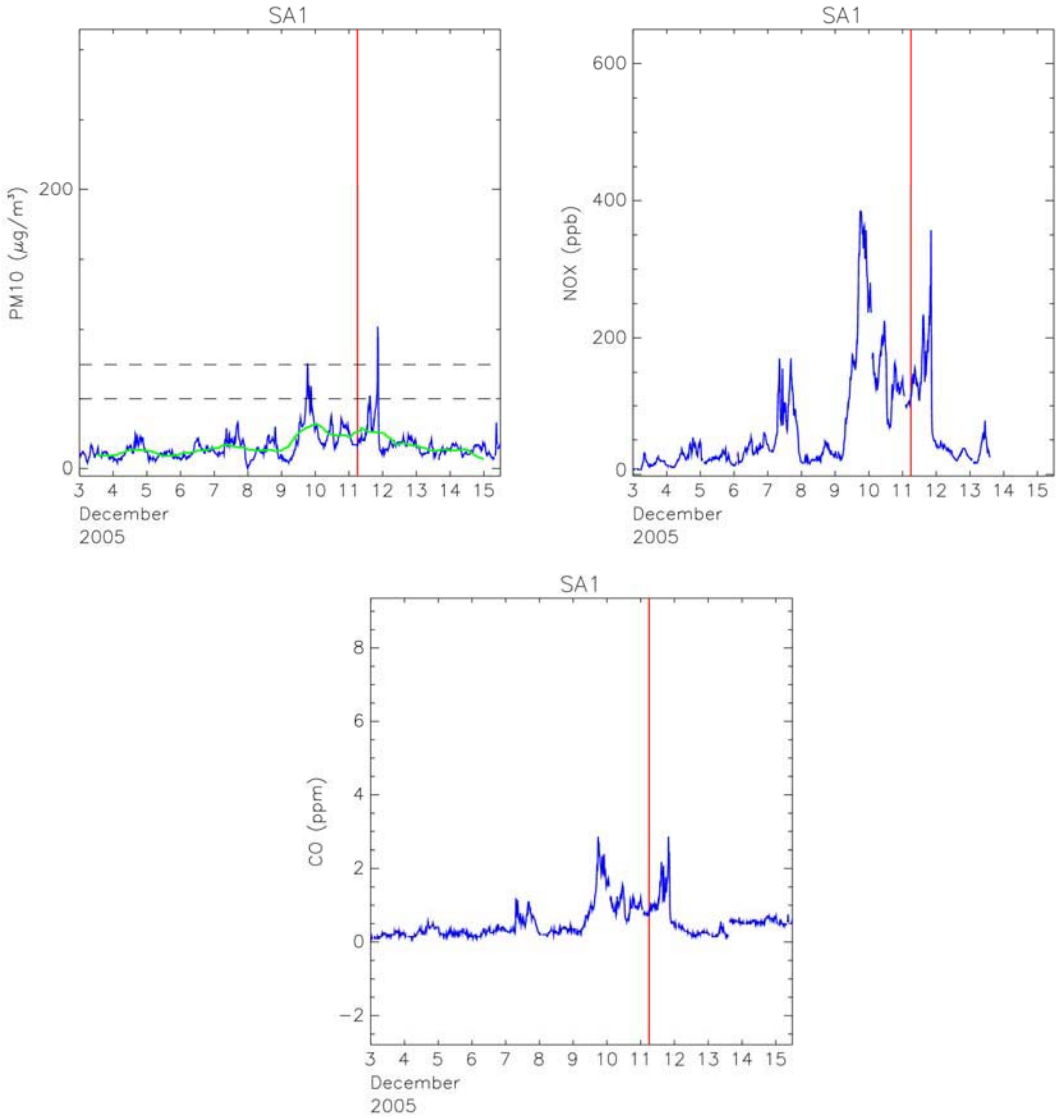


Figure 16: Time series of 15 minute mean concentrations of PM_{10} (in µg m^{-3} (TEOM)), NO_x (in ppb) and CO (SA1 only) (in ppm) at Horsham (HO2), Lewes (LS2), Dorking (MV3) and St Albans (SA1). The red line denotes the time of the explosion at Buncefield. For PM_{10}, 24 hourly rolling mean concentrations are shown in green and are plotted against the mid point of the 24 hour averaging period. Boundaries between the low, moderate and high air pollution bands based on 24 hourly means are highlighted using dashed horizontal lines

From Monday 12th December onwards the risk of grounding was expected to increase due to reduced buoyancy of the plume as fires were extinguished. King's College ERG suggested potential grounding of the plume during Tuesday 13th and Wednesday 14th December at Watford (WF1) and Barnet (BN2) (see Table 4). The air pollution index for PM_{10} was classed as 'low' at these two sites, at this time.

The brief peaks in PM_{10} concentrations on the evening of Sunday 11th December at Horsham, Lewes, Dorking and St Albans are analysed in further detail. A peak 15-minute mean PM_{10} concentration (TEOM) of 223 µg m^{-3} was recorded at Horsham between 22:30 and 22:45Z, Lewes recorded 167 µg m^{-3} between 19:00 and 19:15Z, Dorking measured 120 µg m^{-3} between 16:00 and 16:15Z and St Albans measured 102 µg m^{-3} between 20:15 and 20:30Z.

Netcen studied the ratios of PM_{10} to NO_x concentrations to determine the likely source of the peak in PM_{10} concentrations. In general, increases in PM_{10} concentrations due to traffic emissions would normally be accompanied by increases in other pollutants such as NO_x. Ratios of PM_{10} to NO_x concentrations at Horsham at the time of the peak in PM_{10} concentrations were unusual and therefore suggested that the peak could not totally be explained in terms of traffic emissions.

The origin of the air contributing to the peaks in PM_{10} concentrations at Horsham, Lewes, Dorking and St Albans on Sunday 11th December can be determined by running NAME backwards. Figures 17 to 20 show the history of near surface air arriving at Horsham, Lewes, Dorking and St Albans, respectively, at the time of the PM_{10} peaks, as predicted by NAME. The plots show the history of the air back until the time of the explosion at Buncefield. NAME predicts that near surface air at Lewes and Dorking at the time of the PM_{10} peaks came from the west and hence suggests that the PM_{10} peaks cannot be attributed in any way to the fire at Buncefield. However, NAME predicts that air from Buncefield could have been transported to the ground at Horsham and St Albans and therefore suggests that the Buncefield incident could have contributed to the peaks in PM_{10} concentrations observed at these two locations. The NAME modelling suggest that most of the air contributing to the peaks at these two locations originated from lower levels. In particular NAME suggests that only air originating at the Buncefield site location at a height below 1000 m above ground level could have contributed to these peaks in PM_{10} measurements.

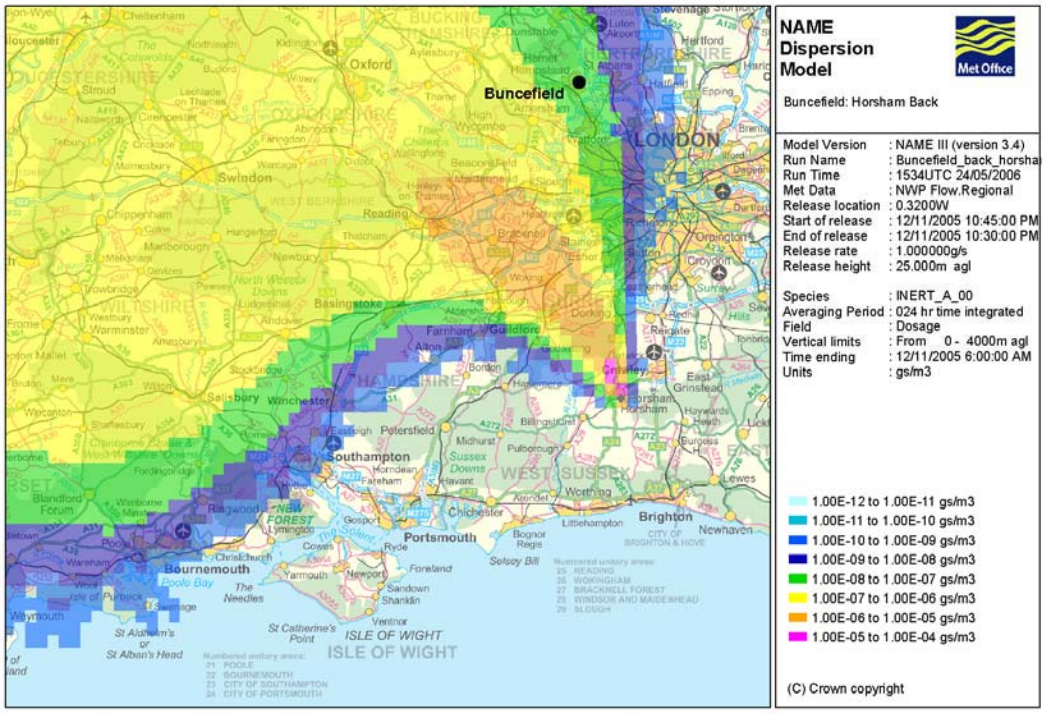


Figure 17: Air history map showing the origin of near surface air arriving at Horsham between 22:30 and 22:45Z on 11/12/05 since the time of the explosion at Buncefield at 06Z on 11/12/05 as predicted by NAME

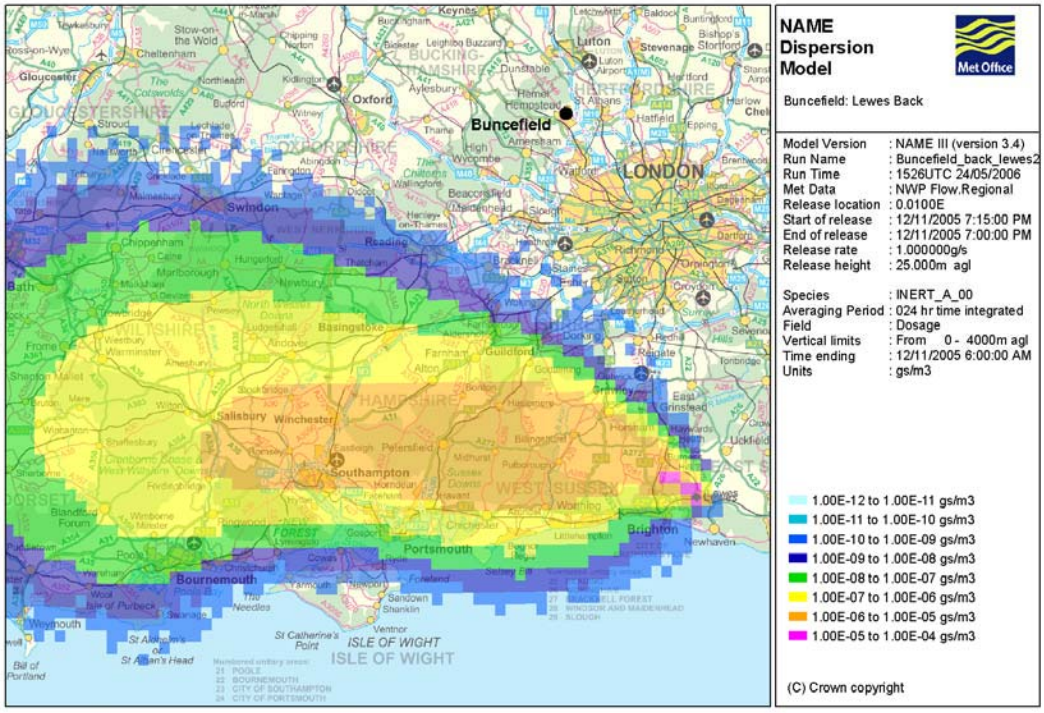


Figure 18: Air history map showing the origin of near surface air arriving at Lewes between 19:00 and 19:15Z on 11/12/05 since the time of the explosion at Buncefield at 06Z on 11/12/05 as predicted by NAME

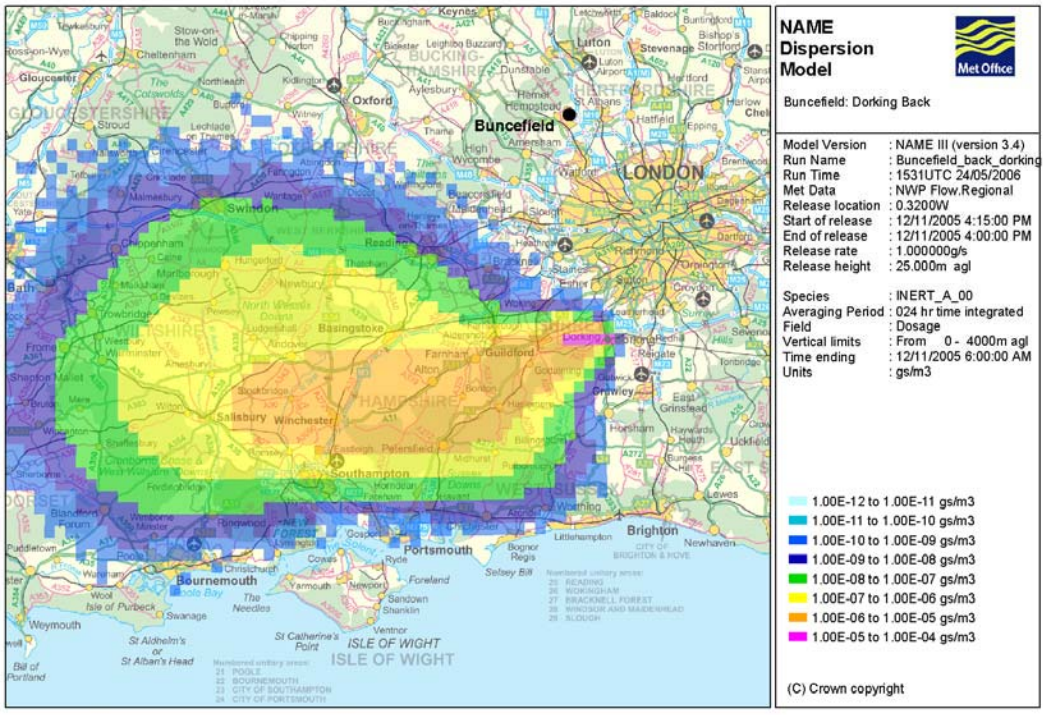


Figure 19: Air history map showing the origin of near surface air arriving at Dorking between 16:00 and 16:15Z on 11/12/05 since the time of the explosion at Buncefield at 06Z on 11/12/05 as predicted by NAME

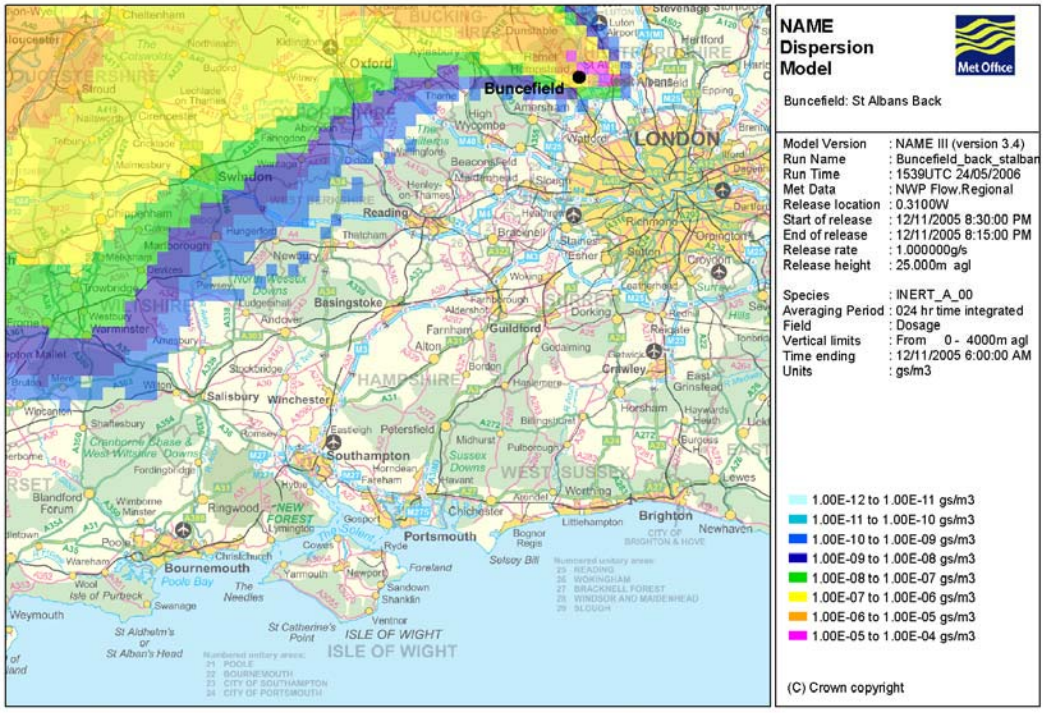


Figure 20: Air history map showing the origin of near surface air arriving at St Albans between 20:15 and 20:30Z on 11/12/05 since the time of the explosion at Buncefield at 06Z on 11/12/05 as predicted by NAME

When NAME is run backwards in this way to identify source regions of near surface air arriving at monitoring sites, the location and time of the measurement is well defined. This is in contrast to forward modelling of the Buncefield incident when there is much uncertainty in the source term (plume rise, etc.). Hence, aside from uncertainties in the model, we have relatively high confidence in the fact that the Buncefield plume did not contribute to the peak PM_{10} measurements at Lewes and Dorking. We have a similar level of confidence in the fact that air at the Buncefield location somewhere between 0 and 4000 m above the ground did arrive at Horsham and St Albans at the time of the peak PM_{10} measurements. However, air could have come from the Buncefield location but have been 'clean' due to it being at a different height within the atmosphere to the plume. Hence due to the uncertainty in the plume rise at Buncefield , there is rather less confidence that the Buncefield plume contributed to the peak PM_{10} concentrations at Horsham and St Albans.

7 Long range transport

Long range modelling of the smoke plume using NAME suggests that once the plume left the UK it was transported over parts of France, Spain and Portugal before clearing over the Atlantic, dispersing as it progressed (see Figure 21). Netcen studied PM_{10} measurements from north-west France and reported that PM_{10} levels in north-west France during the Buncefield incident were classed as low using the UK air pollution index. Higher concentrations were seen on the continent prior to the event (see [11] for further details).

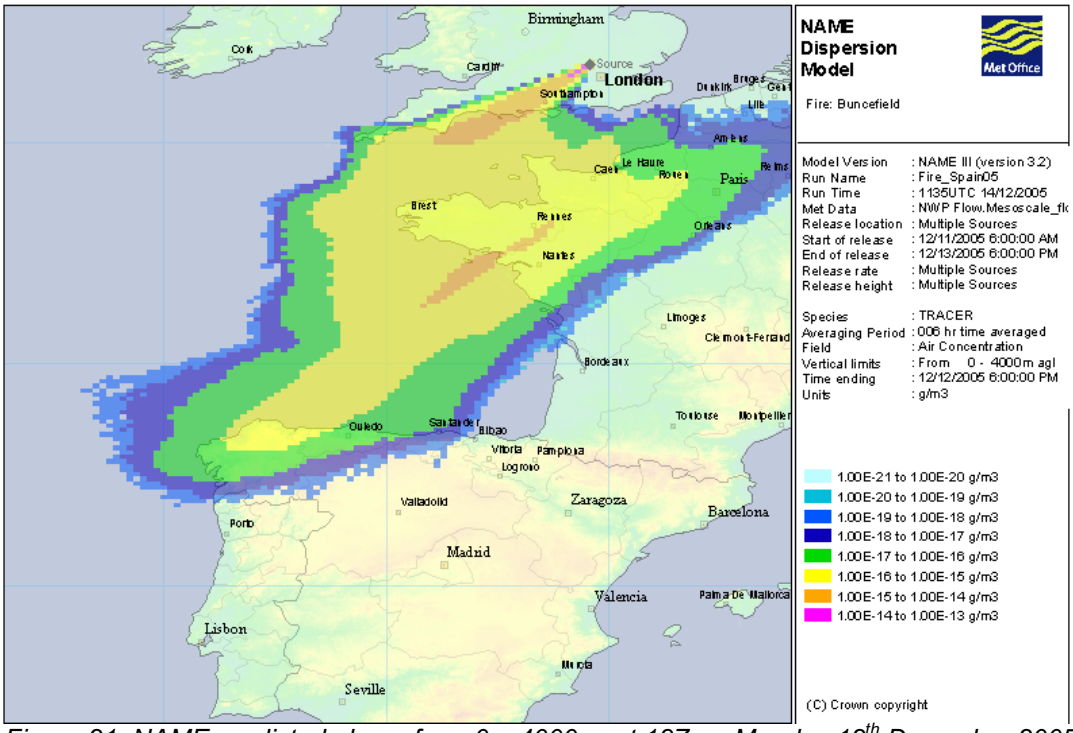


Figure 21: NAME predicted plume from 0 – 4000 m at 18Z on Monday 12th December 2005 showing transport over France and Spain

8 Plume rise

The plume rise scheme within NAME is designed to model the initial rise of plumes with momentum and buoyancy up until the point they become neutrally buoyant or passive [13]. The scheme solves integral conservation equations of mass, momentum and heat and was designed to be used to model plumes from power station stacks. It has never been used to model a source as buoyant and as large as the Buncefield plume before. In addition there is much uncertainty in the input parameters required (emission temperature, initial plume radius and emission velocity). Alongside emission estimates, the heat released during the incident was also estimated by Netcen using the following net calorific values: 44.8 GJ t^{-1} for petrol, 43.9 GJ t^{-1} for kerosene and aviation fuel and 43.3 GJ t^{-1} for DERV and gas oil [3]. A total of 3.6×10^6 GJ was estimated to be released assuming 100% combustion of 105 million litres of fuel.

Assuming a 96 hour release and scaling the heat release rate in the same way as the emission rate estimates (i.e. releasing a total of 3.6×10^6 GJ with relative scaling factors of 1 for Sunday, 0.9 for Monday, 0.4 for Tuesday and 0.2 for Wednesday) gives an estimated heat flux, F_h, of 16.8 GJ s^{-1} on Sunday, 15.1 GJ s^{-1} on Monday, 6.7 GJ s^{-1} on Tuesday and 3.4 GJ s^{-1} on Wednesday. These values are broadly within the range expected from comparisons with other heat sources – a large power station stack emits about 0.6 GJ s^{-1} and the heat flux estimate from the large Chisholm forest fire in Alberta, Canada is 3585 GJ s^{-1} [9].

The plume rise scheme in NAME requires inputs of emission temperature (T_s), initial plume radius (r_s) and emission velocity (w_s). For a buoyancy dominated plume, these three variables are related to the heat flux via

$$F_h = c_p \pi (\theta_s - \theta_a) r_s^2 \rho_s w_s, \quad (2)$$

where c_p is the specific heat capacity of the ambient air at constant pressure, θ_s is the potential temperature of the emission, θ_a is the potential temperature of the ambient air, r_s is the initial plume radius, ρ_s is the density of the emission and w_s is the emission velocity. The density is calculated using the equation of state

$$p = \rho R T.$$

Estimates of near surface pressure (p = 1040 hPa) and near surface ambient temperature (T = 275 K) were assumed based on observations. The values of emission temperature, initial plume radius and emission velocity were chosen to give the estimated heat flux values. Fortunately for this buoyancy dominated plume, the NAME plume rise scheme only appears to be sensitive to the heat flux value and not the individual initial plume radius, emission temperature and emission velocity, which are largely unknown. Indeed the concept of an emission velocity, while a well defined concept for a stack emission, may be ill defined for a fire. A range of cases were modelled varying the plume temperature between 500 and 2000 K and the initial plume radius between 25 and 100 m but with a fixed heat release rate.

Figure 22 shows the NAME predicted six-hourly mean 0 – 4000 m PM_{10} concentration from 06Z – 12Z on Sunday 11th December using a emission rate of 56.1 kg s^{-1} (calculated using the total PM_{10} emissions in Table 2 and the suggested relative scaling factors for each day: 1 for Sunday, 0.9 for Monday, 0.4 for Tuesday and 0.2 for Wednesday) and the NAME plume rise scheme with a heat flux of 16.8 GJ s^{-1} (T_s = 1000 K, r_s = 50 m, w_s = 8.19 m s^{-1}). Comparing Figure 22 with the satellite imagery in Figure 2 we see that NAME does not spread the plume enough. In particular, the plume rise achieved using the NAME plume rise scheme only transports the plume to a height of approximately 1750 m above ground level and therefore does not capture the transport of the plume southwards and, at higher levels, south-westwards. Figure 23 shows the NAME predicted six-hourly mean 0 – 4000 m PM_{10} concentration from 06Z – 12Z on Sunday 11th December using the same emission rate but a larger heat flux of 67.2 GJ s^{-1} (i.e. four times larger). The plume rise achieved in this case is a height of approximately 2750 m above ground level and is more in line with that observed. The transport of the plume at higher levels south-westwards is now captured by NAME but, as in Figure 22, the vertical spread of the plume is too small and consequently the transport of the plume at lower levels south-eastwards is now not modelled.

Given the uncertainties involved, namely the amount and rate of fuel burnt and the heat released per unit mass / volume of fuel, large errors in the estimated heat release rate on Sunday 11th December are possible. There are however, other possible reasons for the insufficient plume rise obtained by NAME and the poor vertical spread of the plume cannot be improved by increasing the heat release rate estimate.

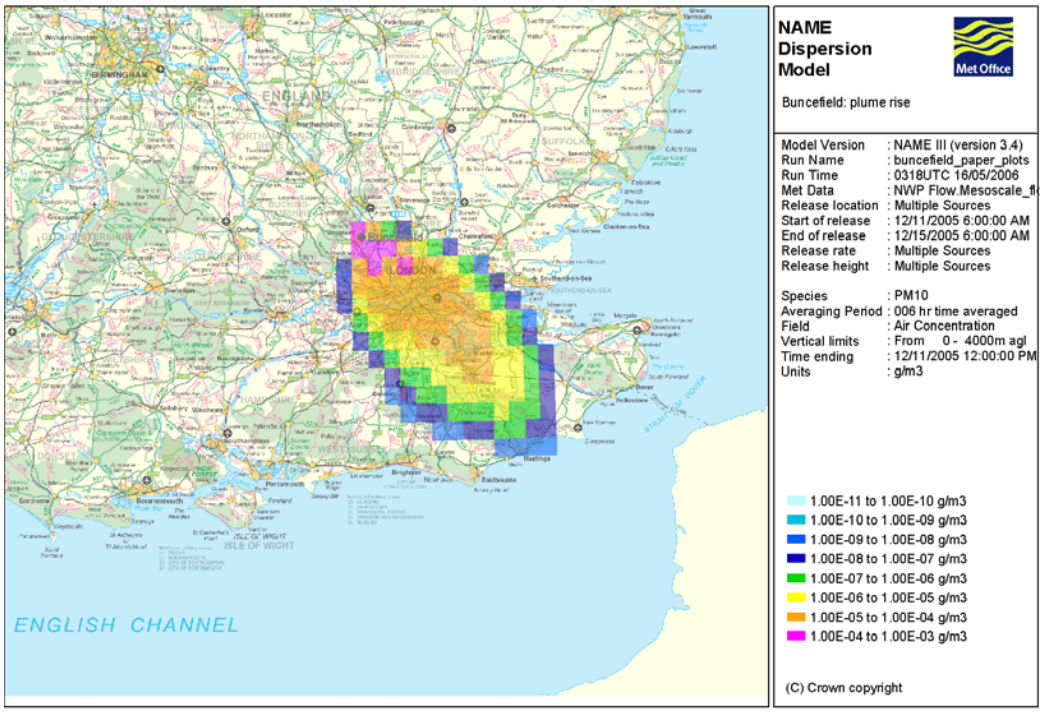


Figure 22: NAME predicted six-hourly 0 – 4000 m mean PM_{10} concentrations from 06Z to 12Z on Sunday 11th December 2005 calculated using the plume rise scheme with a heat flux of 16.8 GJ s^{-1}

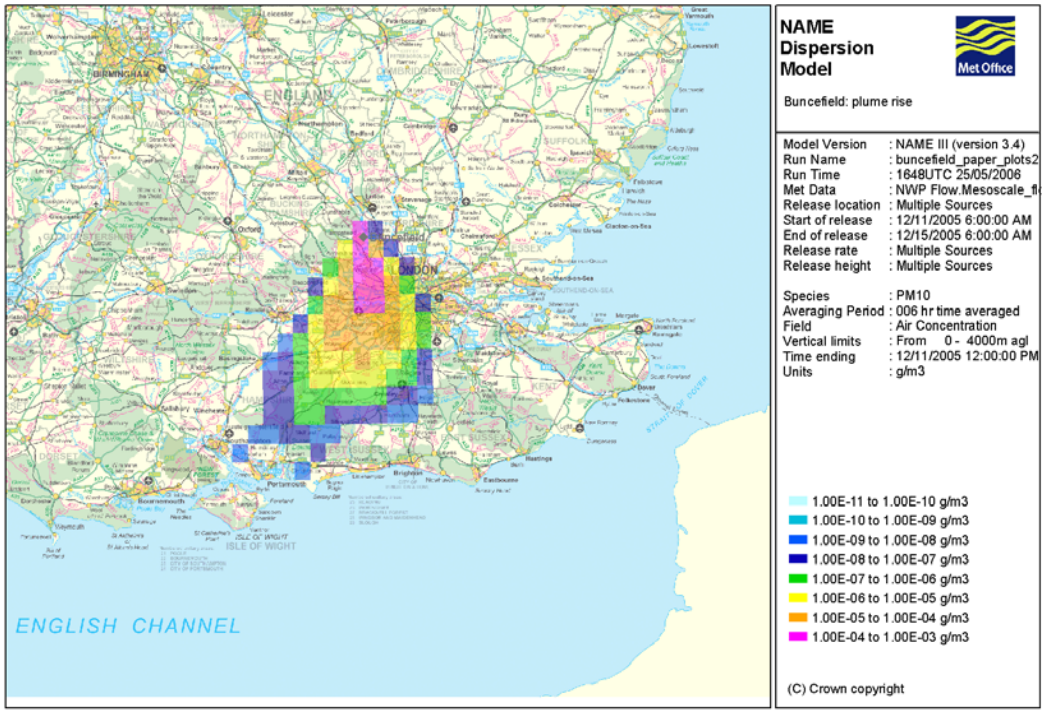


Figure 23: NAME predicted six-hourly 0 – 4000 m mean PM_{10} concentrations from 06Z to 12Z on Sunday 11th December 2005 calculated using the plume rise scheme with a heat flux of 67.2 GJ s^{-1}

Luderer et al. [9] studied the large Chisholm forest fire in Alberta, Canada and found that the energy budget was dominated by the release of latent heat from condensing water vapour from entrained water from the ambient air. The atmospheric conditions on Sunday 11th December had high levels of relative humidity (see Appendix A) with reports of thick fog in places. Hence latent

heat released from entrained moisture may have had a significant contribution to the energy budget. NAME does not take into account the release of latent heat from condensing water vapour and this may explain why the estimated model plume rise is insufficient. It is hoped that the effects of latent heat release on the plume rise can be studied using a large eddy model (LEM). It is worth noting, however, that the FAAM aircraft did not detect condensation within the plume on Tuesday 13th December.

Herring and Hobbs [6] studied a smoke plume from the 1991 Kuwait oil fires and suggested that absorption of solar radiation could lead to additional heating within the plume causing radiatively driven lofting. NAME does not take into account this increase in the energy budget due to absorption of solar radiation by the black carbon. To quantify this effect, the detailed microphysical properties of the smoke plume aerosol measured by the FAAM aircraft were included in radiative transfer calculations under cloud-free conditions using appropriate atmospheric profiles of temperature, humidity, and other gaseous constituents and appropriate solar insolation and solar zenith angles. Irradiance measurements from the FAAM aircraft on Tuesday 13th December showed that 100 W m^{-2} of the solar radiation flux was absorbed by the plume at a distance of approximately 78 km downwind of the source and this was used within the radiative transfer calculation to constrain the amount of aerosol within the plume. The radiative transfer calculations indicate that the top of the plume was subject to an additional radiatively driven heating rate of 0.34 K hr^{-1}. The top of the plume experiences the strongest radiatively driven lofting, thus potentially stretching the vertical extent of the plume. Rough estimates suggest relatively modest increases in the plume top by 60 m and in the plume depth by 40 m during the first hour after release, due to absorption of solar radiation. This effect was also simulated with NAME using a simple constant and horizontally homogeneous meteorological field. The results showed that the additional rise due to absorption of solar radiation was approximately 30 m per hour (assuming an absorbed solar radiation flux of approximately 280 W m^{-2} - the total solar radiation observed by the FAAM aircraft). These two estimates suggest that only a modest rise of the plume can be attributed to lofting.

The Buncefield plume was characterised by a number of smaller plumes from individual tank fires which combined, due to their close proximity, to give the appearance of a single plume. It has been said that satellite imagery from Sunday 11th December appears, at times, to suggest that there were two separate plumes which joined up or overlapped over London (see Figure 2). NAME, however, models the Buncefield plume as a single plume from a uniform source. It is possible that the spatial variation in the plume's properties as the smaller plumes from the individual fires combine and reinforce each other may result in a larger vertical spread than is predicted with NAME.

Other possible explanations as to why NAME does not show the observed plume rise and vertical spread of the plume include the possibility that the input meteorological data (from the Unified Model) does not accurately

capture the atmospheric meteorological situation. The plume rise will be particularly sensitive to the atmospheric temperature profile.

9 "What if?" scenarios

It has been said that the meteorological conditions had a significant influence on the ground level effects of the Buncefield plume keeping most of the plume trapped aloft and suppressing vertical mixing. In addition, opinions are that we were very lucky and that, if the incident had happened at another time of the year, the effects at ground level would have been much greater. On the other hand, it has also been suggested that the calm stable atmospheric conditions allowed the flammable mixture of released fuel and air to pool and the explosion may not have even occurred in different meteorological conditions. We study, using NAME, the predicted effects of the Buncefield incident if it were to have taken place in different meteorological conditions: strong winds, convective conditions and during periods of significant precipitation. These meteorological situations are chosen since they are thought to be those in which the ground level effects of the Buncefield plume may be the greatest. In convective conditions, the boundary layer is well mixed and is much deeper, growing to heights of 1 – 2 km during the daytime. It is therefore possible that more of the plume would be present within the boundary layer either through being trapped by the temperature inversion at the boundary layer top or by re-entrainment as the convective boundary layer grows (fumigation). In addition, relatively high ground level concentrations could be experienced if the plume was caught in a convective downdraft. In strong winds, the plume will bend over and entrainment of ambient air into the plume will be increased, thus reducing the rise of the plume. In wet conditions, the deposition of the plume material is expected to be greatest since wet deposition is a much more efficient process than dry deposition.

The plume rise is very much dependant on the meteorological conditions; therefore it is necessary to use the plume rise scheme to model the "what if?" scenarios. A constant PM_{10} emission rate of 56.1 kg s^{-1} is modelled based on the estimated release rate on Sunday 11th December (i.e. we assume that there were no fire fighting activities). An emission velocity of 6.89 m s^{-1}, an initial plume radius of 50 m and an emission temperature of 2000 K were used based on an estimated heat flux of 16.8 GJ s^{-1}. We note that this estimated heat flux did not give a large enough plume rise or vertical spread of the modelled plume compared to that observed on Sunday 11th December (see Figure 22). However, the possible reasons for this have already been discussed and extend beyond errors in the source properties. The errors may, for example, be in the input meteorological data and hence tuning the source properties is not necessarily appropriate. We also note that, for different ambient conditions, the above source properties will result in different heat flux values. The sensitivity of Equation (2) to ambient surface pressure and temperature is, however, small and so we expect this difference to be relatively minor. Caution, however, should be exercised since these modelled scenarios are based on values (e.g. emissions) on which there is considerable uncertainty.

There was also some discussion during the initial stages of the incident as to whether the fire should be left to burn or tackled using fire fighting equipment, foam and water. We therefore, compare predicted maximum hourly averaged PM_{10} boundary layer concentrations from the incident (Figure 25) with those predicted if the fire was to burn uncontrolled at the same initial rate for 7 – 10 days (Figure 26). We note that at the estimated emission rate of 56.1 kg s^{-1}, the fire would only have continued to burn for 2.5 days before fuel was exhausted (based on estimated total emissions). We are able, however, in directly comparing the maximum predicted PM_{10} boundary layer concentration, to determine the relative effects of a fire burning at a constant rate at any point over the period 11th to 21st December 2005.

We see that meteorological conditions were extremely favourable on Sunday 11th December resulting in low boundary layer concentrations (Figure 24). Over the whole incident the maximum hourly averaged concentrations were predicted to occur near to the source and occurred later on in the incident when meteorological conditions became less favourable. If the fire had been allowed to burn uncontrolled for 7 – 10 days, NAME predicts that the maximum hourly averaged boundary layer concentrations would have been higher. The spatial peak of the maximum hourly averaged boundary layer concentrations was predicted to be approximately 50% higher than that experienced during the event.

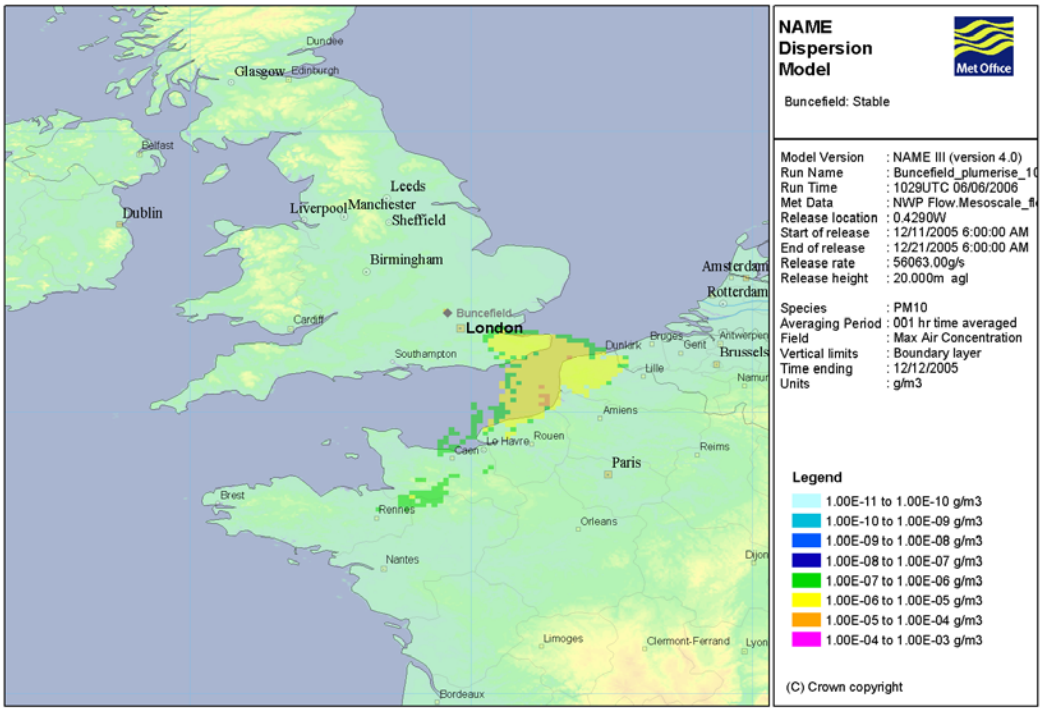


Figure 24: NAME predicted maximum hourly averaged PM_{10} boundary layer concentrations from 06Z on Sunday 11th December until 00Z on Monday 12th December

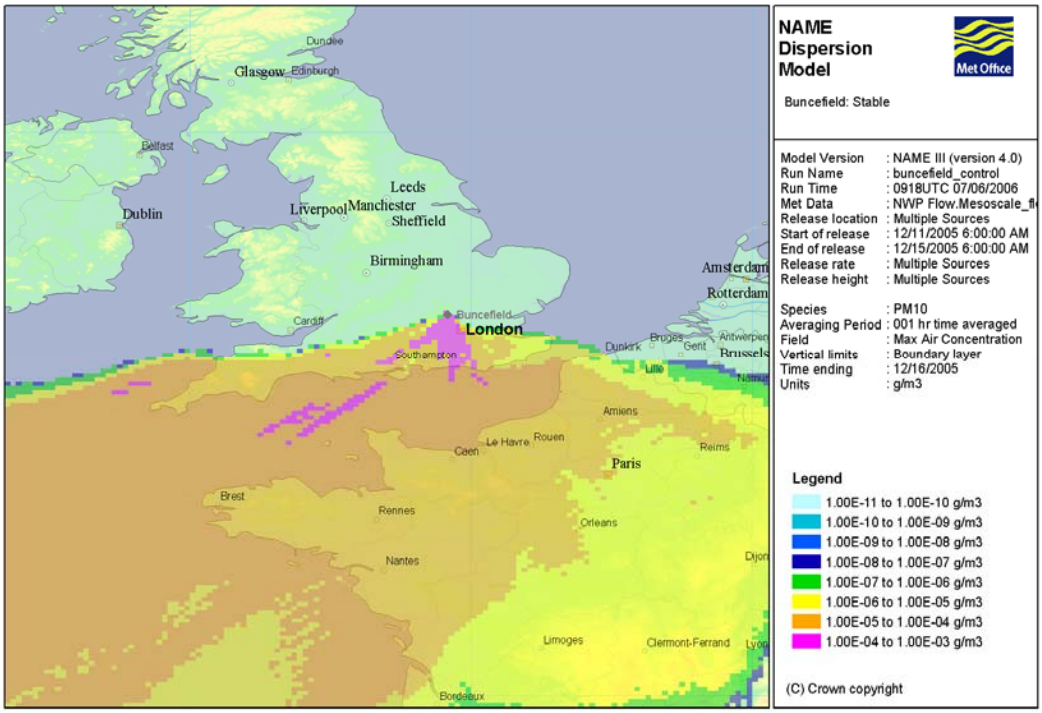


Figure 25: NAME predicted maximum hourly averaged PM_{10} boundary layer concentrations during the Buncefield incident

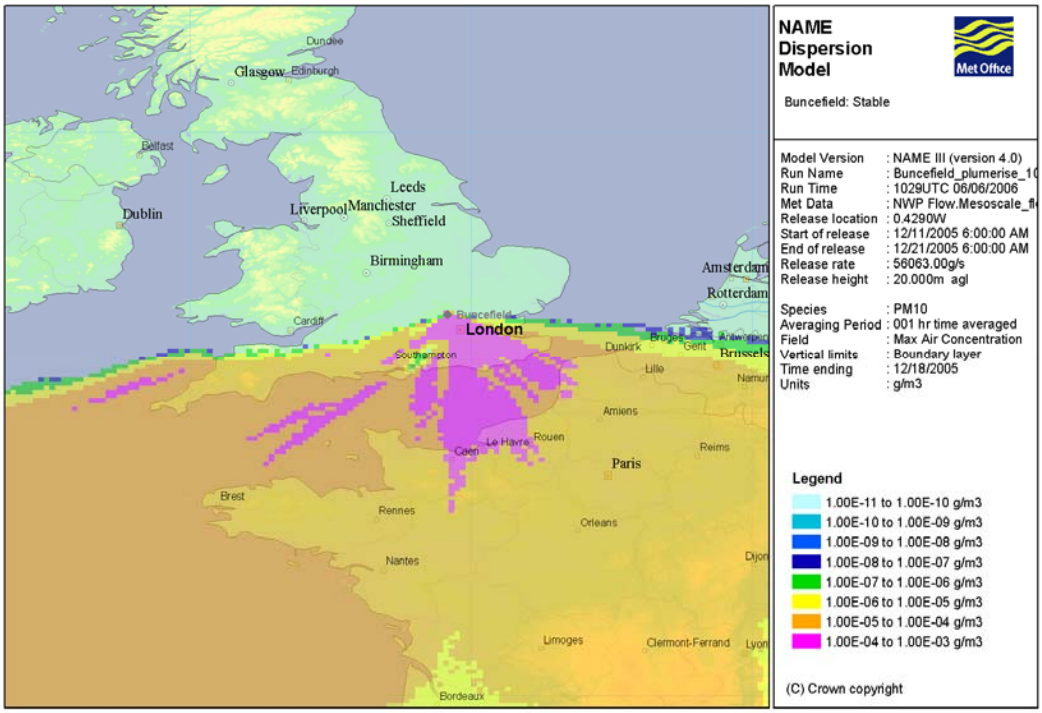


Figure 26: NAME predicted maximum hourly averaged PM_{10} boundary layer concentrations assuming the fire was allowed to burn uncontrolled for 7 – 10 days

For the strong winds scenario, the period 17th to 30th May 2006 was chosen. During this period a succession of Atlantic low pressure systems gave an unsettled period to England with heavy rain and strong winds at times with coastal gales. We compare predicted maximum hourly averaged PM_{10} boundary layer concentrations over this period (Figure 27) with predicted maximum hourly averaged PM_{10} boundary layer concentrations on Sunday

11th December (Figure 24) and over the time of the incident (Figure 25). In windy conditions, maximum hourly averaged PM_{10} boundary layer concentrations were predicted to be higher than those experienced during the incident. The spatial peak of the maximum hourly averaged boundary layer concentrations over the period 17th – 30th May 2006 was predicted to be approximately 25% higher than the predicted peak maximum hourly averaged boundary layer concentration during the actual event. The reason that it is not higher is probably due to the fact that the strong winds also result in more along plume spread.

For the convective case, the period 2nd to 16th August 2003 was chosen since high temperatures, regularly exceeding 30 ºC in central England, were experienced during this period. Maximum hourly averaged PM_{10} boundary layer concentrations predicted over this convective period are shown in Figure 28. The peak maximum hourly averaged PM_{10} boundary layer concentration was predicted to be the highest of all the scenarios studied and was approximately 90% higher than the predicted peak maximum hourly averaged boundary layer concentration during the actual event.

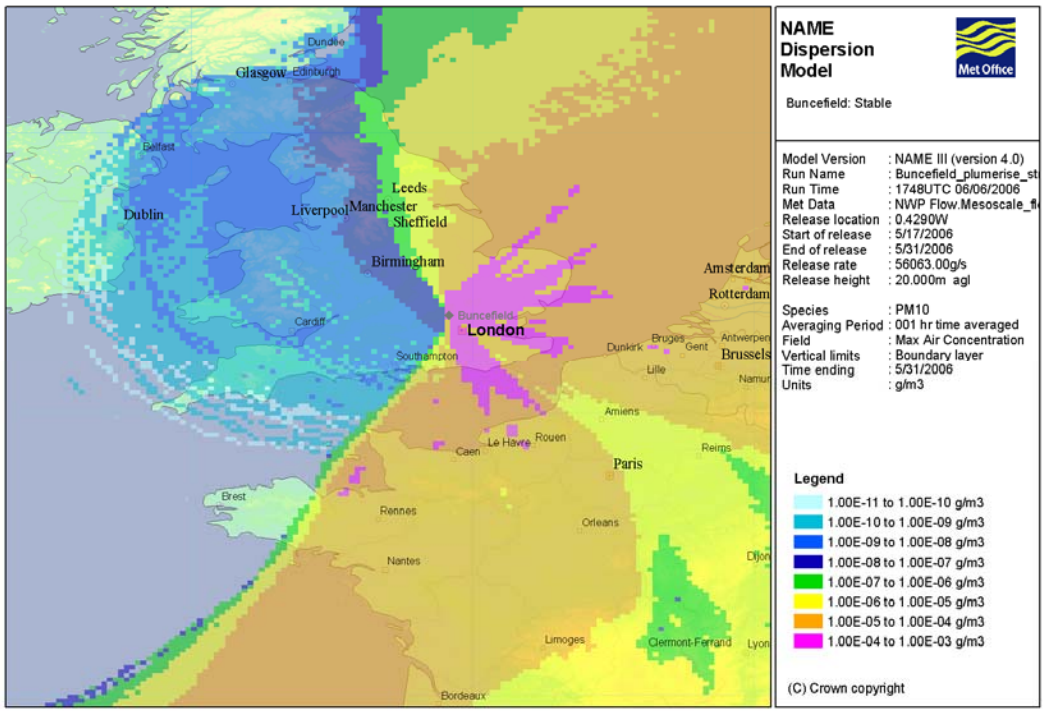


Figure 27: NAME predicted maximum hourly averaged PM_{10} boundary layer concentrations if the fire had occurred in windy conditions over the period 17th – 30th May 2006

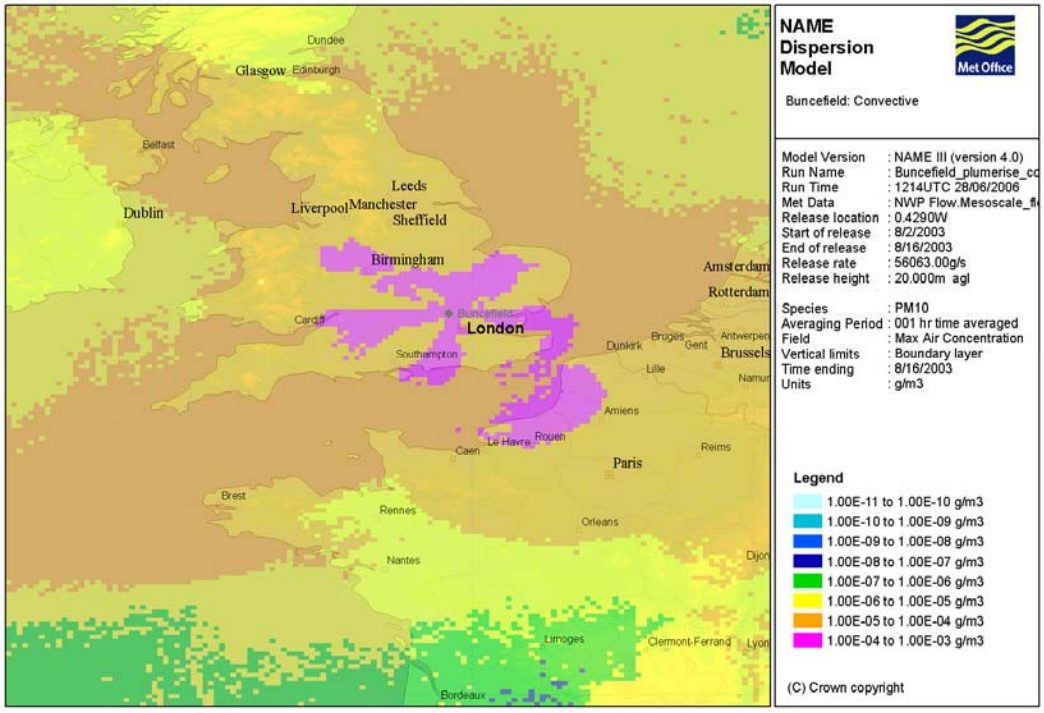


Figure 28: NAME predicted maximum hourly averaged PM_{10} boundary layer concentrations if the fire had occurred in convective conditions over the period 2nd – 16th August 2003

NAME predicts that the high buoyancy of the Buncefield plume would have resulted in a substantial quantity of the plume escaping from the boundary layer even in these alternative meteorological scenarios. This could explain why the predicted ground level effects from Buncefield are not substantially worse for these meteorological conditions.

We note that the “What if?” scenarios in other meteorological conditions often appear to show that a larger area is affected. One must not be mislead by this observation since the model runs for the “What if?” scenarios often cover a longer period in time and this will obviously influence the area affected. To compare the relative size of the affected areas, one would do better to compare dosage plots (time integrated concentrations) for runs of equal periods of time.

9.1 Deposition

In addition to air concentration there is interest in deposition of material from the fire. Fortunately, during the Buncefield oil depot incident, the meteorological conditions were mainly dry thereby limiting deposition of material from the plume. Deposition would potentially have been much greater if there had been significant amounts of precipitation during the incident. We compared the predicted deposition of PM_{10} from the incident with the predicted deposition if the incident had occurred during a wet period from 18Z on 23rd October 2005 to 12Z on 25th October 2005. Low pressure dominated this period bringing unsettled weather with showers and longer spells of rain to the UK. During this 42 hour period, the Unified Model has a total of 30 mm of rain at the Buncefield oil depot location. Since deposition is cumulative, the

predicted deposition fields are compared against those from a similar length period during the actual event, namely 06Z on Sunday 11th December until 00Z on Tuesday 13th December.

For this study the deposition modelling in NAME of PM_{10} does not take into account gravitational settling. Wet deposition is modelled using

$$m\left(1-\exp\left(-\Lambda\Delta t\right)\right),$$

where m is the mass of pollutant, Λ is the scavenging coefficient and Δt is the computational time step [10]. The scavenging coefficient, Λ, is defined by

$$\Lambda = Ar^{B},$$

where A and B are coefficients defined for different types of precipitation (e.g. convective, dynamic, rain and snow) and different deposition processes (e.g. rainout, washout, orographically enhanced precipitation). Dry deposition is modelled using the concept of a deposition velocity, v_d, calculated using a resistance analogy parameterisation,

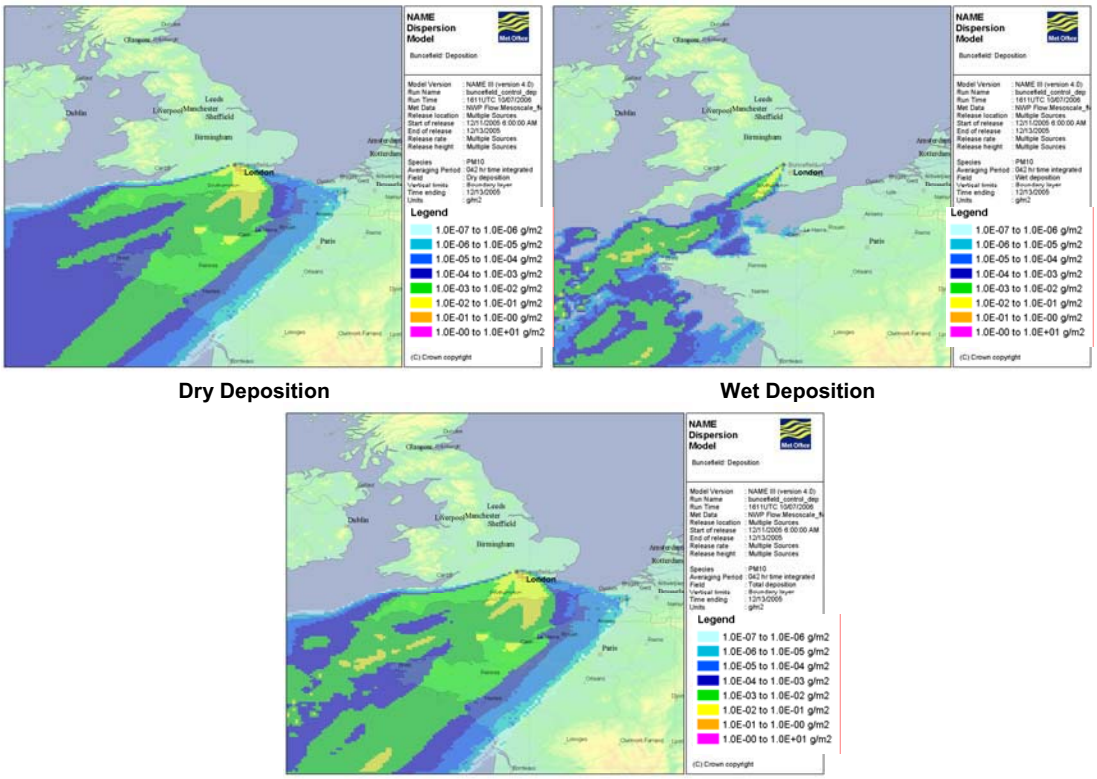
$$v_d = \frac{1}{R_a + R_b + R_c},$$

where R_a is the aerodynamic resistance, R_b is the laminar layer resistance and R_c is the surface resistance. For PM_{10}, R_c is taken to be 1000 $(m\ s^{-1})^{-1}$. R_a and R_b are calculated within the model and depend on the meteorological conditions. Dry deposition is applied to pollutant in the boundary layer and is calculated using

$$m\left(1-\exp\left(-\frac{v_d}{h}\Delta t\right)\right),$$

where m is the mass of pollutant, h is the boundary layer depth and Δt is the computational time step.

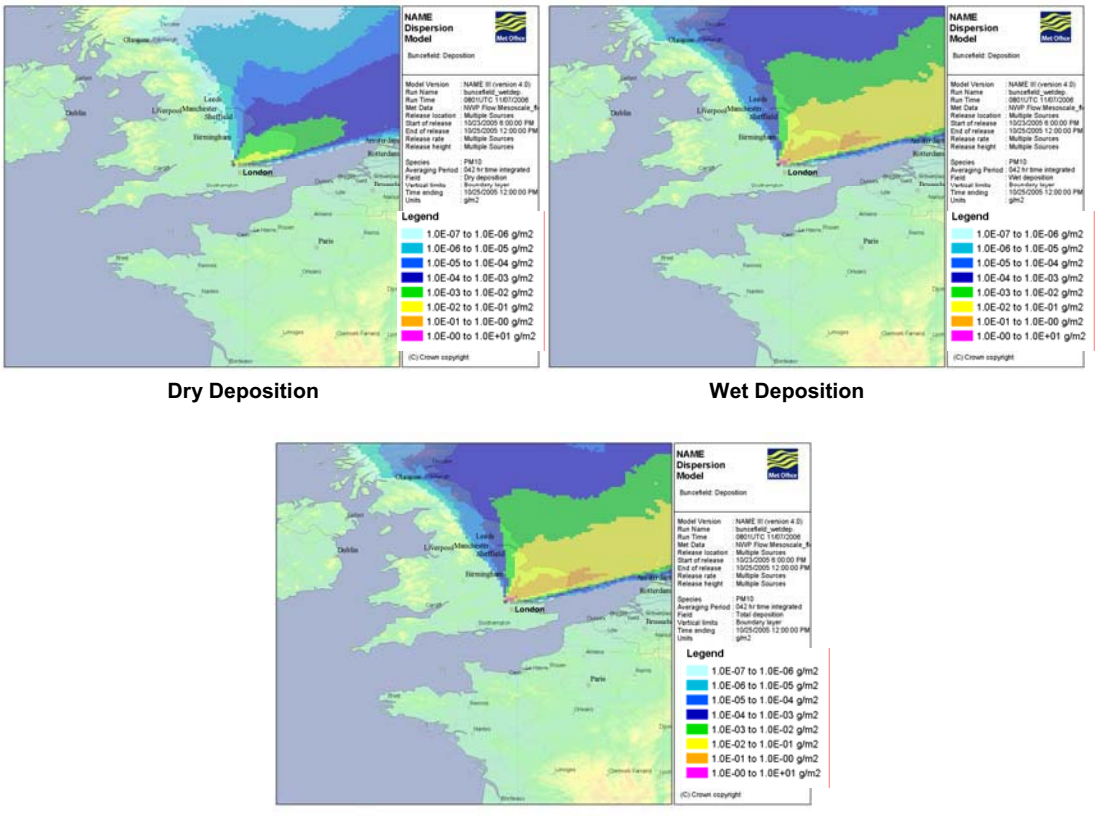
Figure 29 shows the predicted wet, dry and total deposition of PM_{10} from 06Z on Sunday 11th December until 00Z on Tuesday 13th December during the Buncefield incident. The predicted maximum dry deposition value over this 42 hour period was 0.376 g m^{-2} and occurred near to the source. Wet deposition contributed much less to the predicted total deposition with a maximum wet deposition value of 0.0491 g m^{-2}, again near to the source. In comparison, Figure 30 shows the predicted dry, wet and total deposition if the event had occurred over the wet period from 18Z on 23rd October to 12Z on 25th October 2005. The predicted total deposition of PM_{10} is dominated, in this case, by wet deposition with a maximum wet deposition value of 2.25 g m^{-2}. Dry deposition is much less over this period with significant rainfall with a maximum dry deposition value of 0.0719 g m^{-2}. The predicted maximum total deposition over the period with significant precipitation is roughly 6 times greater than the predicted maximum total deposition over a similar length of time from the actual Buncefield incident.



Dry Deposition **Wet Deposition**

Total Deposition

Figure 29: NAME predicted wet, dry and total deposition of PM_{10} over the period from 06Z on Sunday 11th December to 00Z on Tuesday 13th December 2005



Dry Deposition **Wet Deposition**

Total Deposition

Figure 30: NAME predicted wet, dry and total deposition of PM_{10} if the Buncefield incident had occurred over a period of significant precipitation from 18Z on 23rd October to 12Z on 25th October 2005

10 Conclusions

Modelling of the plume from the Buncefield oil depot explosion on Sunday 11th December 2005 proved to be of great help to the emergency response effort during the incident by forecasting the transport and spread of the plume over time and identifying those regions most at risk if grounding of the plume were to occur. The plume was predicted to have travelled over a region roughly south-eastwards through to south-westwards from the depot covering areas of southern England, France, Spain and Portugal. Emission estimates and observations enabled subsequent refinement of the plume modelling to predict likely concentrations within the plume and at ground level.

Observations were key inputs into guiding the modelling exercises and validating model results. On Sunday 11th December, satellite imagery proved to be invaluable in determining the height to which the buoyant plume was rising in the atmosphere. This was possible due to the fact that there was significant amounts of wind shear present in the atmosphere with the plume being transported south-eastwards at lower levels and south-westwards at higher levels. The FAAM aircraft provided the only in-situ measurements taken from within the plume. These measurements suggests that the main constituent was back carbon (soot); levels of hydrocarbons were low, there was no evidence of poly aromatic hydrocarbons (PAHs) or significant levels of organic particles and levels of CO were not significantly high. $PM_{2.5}$ concentrations within the plume on Tuesday 13th December were estimated using data from the aircraft to be 461 µg m^{-3} over the source with an uncertainty ranging from 290 – 572 µg m^{-3}. In addition, the aircraft provided useful information on the height of the plume within the atmosphere on Tuesday 13th December which was incorporated into modelling exercises. Air quality monitoring provided guidance on grounding of the plume and on potential public exposure to the plume. Specific monitoring undertaken by Netcen in and around the Buncefield oil depot site during the event showed that PM concentrations were high near to the source (~200 m from the fire) particularly directly under the plume. Maximum 15-minute mean PM_{10} concentrations measured were approximately 340 µg m^{-3}. Routine air quality monitoring did not record any unusually high levels which could be attributed to the Buncefield plume. Brief peaks in PM_{10} levels were recorded at a number of monitoring sites. Concentration levels were, however, not extraordinary; in fact, higher levels were measured at monitoring sites in the week before the event occurred. In terms of the UK air pollution index, PM_{10} levels over the affected area remained ‘low’ throughout except at Horsham Roadside and Lewes 2 Roadside where ‘moderate’ levels were recorded. NAME has been used to study the history, since the time of the explosion, of near surface air arriving at the monitoring sites at the time of the PM_{10} peaks. This modelling suggests that the Buncefield plume could have contributed to the peak PM_{10} levels measured at Horsham and St Albans on Sunday 11th December but did not affect peak measurements at Lewes and Dorking.

The meteorology and the high buoyancy of the plume had a significant influence on the incident. At the time of the explosion the atmosphere was

stably stratified with light winds. The high buoyancy of the plume resulted in the plume rising vertically to heights up to 3 km where it was, in the main, trapped aloft with minimal mixing down to ground. Additional modelling of the plume to try and model the initial rise of the plume due to buoyancy was undertaken. The plume rise scheme within NAME was designed to model plumes from power station stacks and has not been tested before to model such a highly buoyant plume. Estimates of the heat release rate from the Buncefield fire were used to run NAME with its plume rise scheme. Comparisons with satellite imagery show that NAME does not then capture the extent of the vertical spread of the plume and, in particular, there is insufficient plume rise. Potential reasons for this have been discussed and include: (1) The source is complex with multiple plumes from many fires which combine and reinforce each other whereas in NAME a single simple plume is modelled. (2) Lofting of the plume from absorption of solar radiation by the black carbon may be important but is not taken into account by the NAME plume rise scheme. (3) Release of latent heat due to condensation of water vapour may be an important contribution to the energy budget but is again not taken into account by the NAME plume rise scheme, and (4) there are potential inaccuracies in the input meteorology (from the Unified Model), in particular, the atmospheric temperature profile. Work on these aspects is continuing where possible.

Meteorological conditions were favourable on Sunday 11th December resulting in low ground level concentrations. Modelling work has predicted the likely ground level concentrations if the Buncefield incident had occurred in different meteorological conditions. Higher ground level concentrations are predicted if the fire had been allowed to continue to burn uncontrolled and in windy and in convective meteorological conditions. The highest ground level concentrations from those scenarios studied were predicted to occur in convective conditions with maximum hourly averaged boundary layer concentrations roughly twice those predicted for the actual event. The deposition of material to the ground was limited due to the lack of precipitation during the incident and due to the elevated plume. The predicted deposition of PM_{10} if the incident had occurred during a period of significant precipitation was six times greater than that predicted during the actual incident.

There are many uncertainties, potentially forever un-resolvable, which affect the accuracy of the modelling. In particular, there is considerable uncertainty in the amount of fuel on site at the time of the explosion, the amount of fuel that was burnt during the incident, the rate at which fuel was burnt, the emission estimates for uncontrolled burning of refined fuel, the amount of heat released, the upper and lower vertical limits of the plume and how all these variables changed over time. The accuracy of modelling exercises in such incidents could be substantially improved by providing a better communication route between those on site, the decision makers and experts in such incidents and the modellers who require accurate input information for their models. Regular updates on the upper and lower vertical limits of the plume, the number of tanks on fire and other visual observations would have enabled more accurate modelling.

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Key

B[a]P Benzo-(a)-Pyrene
BPA British Pipeline Agency
HOSL Herts Oil Storage Ltd

I-TEQ International Toxicity Equivalents
NAEI National Atmospheric Emissions Inventory
NMVOC Non methane volatile organic compounds
TEOM Tapered Element Oscillating Microbalance
UKPIA UK Petroleum Industry Association

Acknowledgements

Thanks are due to Netcen and King's College London Environmental Research Group for access to their measurement data. Contributions both during the event and in the subsequent post-event analysis, from members of the atmospheric dispersion group, the observations based research group and EMARC, Met Office, are gratefully acknowledged.

Appendix A

A1 Meteorological Summary

The nearest available routine surface meteorological observations taken during the Buncefield incident are from Heathrow (51.483ºN, 0.450ºW) and Northolt (51.550ºN, 0.417ºW) (see Figure A.1). Hourly observations from these two locations are shown in black in Figures A.2 and A.3. In addition, high temporal resolution surface observations from the Meteorological Research Unit (MRU) at Cardington (52.100ºN, 0.417ºW) are available as 30, 10 and 1 minute mean values at heights of 10, 25 and 50 m above ground level. Thirty minute mean observations at a height of 10m at Cardington are shown in Figure A.4. Throughout the incident, routine upper air radiosonde observations were available from Herstmonceux (50.900ºN, 0.317ºE) (shown in Figure A.5) and Nottingham (53.000ºN, 1.250ºW) at 00Z and 12Z.

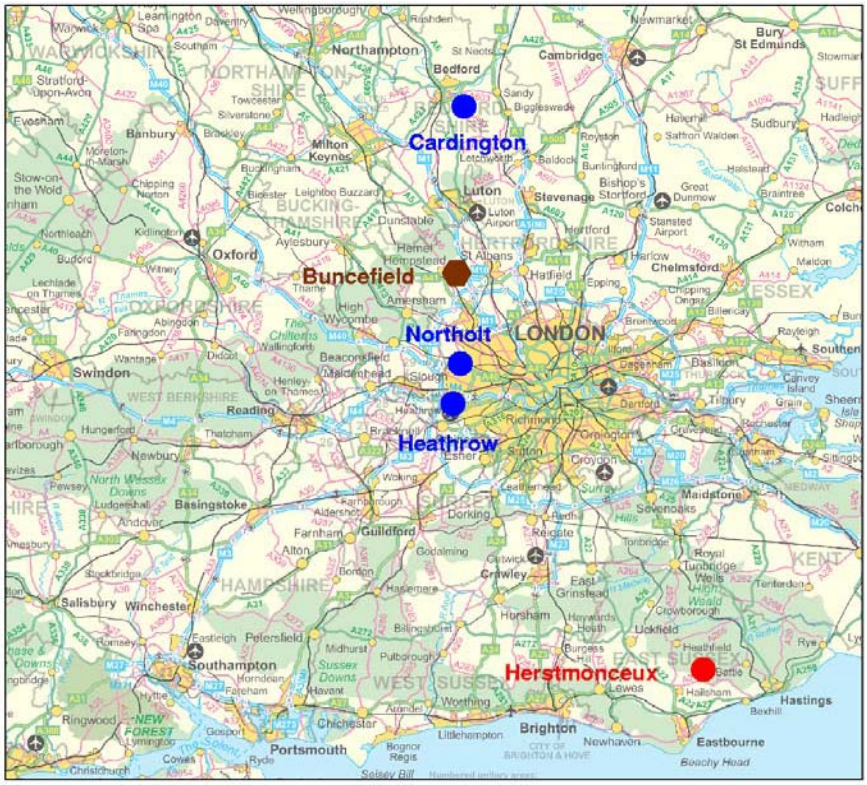

Figure A.1: Locations of Heathrow, Northolt, Cardington and Herstmonceux meteorological observations sites

High pressure dominated the meteorological conditions during the incident. Sunday 11th December was a cold clear day with temperatures below freezing at 06Z at Heathrow and Northolt. Daytime temperatures reached a maximum of 4ºC. Radiosonde ascents at Nottingham and Herstmonceux show a stable atmosphere with consequently very little turbulent mixing. Winds were very light and of variable direction with significant vertical wind shear. High atmospheric relative humidity levels, poor visibility and low level cloud are consistent with reports of thick fog which was evident as white patches on satellite imagery. In general, Sunday was a dry day with just a small amount of rain observed at Heathrow at 13Z.

On Monday 12th December a weak front passed through during the morning; observations at Heathrow and Northolt show no associated precipitation although observations from Cardington suggest that there was a small amount of rain. Winds increased temporarily to moderate and were from a north-easterly direction. Temperatures and cloud amount began to increase and atmospheric relative humidity levels started to fall.

During Tuesday 13th December, winds backed to a north-westerly direction and atmospheric pressure started to fall. Tuesday was a cloudy but dry day. On Wednesday 14th December, winds veered to a northerly and then backed to a westerly direction. Wednesday was also a cloudy but dry day. Temperatures continued to rise and pressure continued to fall, as did atmospheric relative humidity.

Figures A.2 and A.3 show the comparison between observed meteorology (shown in black) and Unified Model meteorology (shown in red) at Heathrow and Northolt. The passage of the front during the morning of Monday 12th December is evident in the observations with a sudden increase in wind speed and change in wind direction. In general, the Unified Model captures the meteorological situation reasonably well over the period. The anemometer at Northolt, with a start-up speed of about 5 knots (~2.6 m s^{-1}), appears to have been stalled for most of Sunday 11th December and the early hours of Monday 12th December when winds were light thereby recording calms in the main. At Heathrow, the Unified Model over-predicts the wind speed during this period of light winds. (The anemometer at Heathrow has a smaller start-up speed of about 1 knot (0.5 m s^{-1}).) This over-prediction of wind speed will result in extra dispersion of the plume by NAME during this time. In addition the UM predicts additional brief periods of small amounts of precipitation from Monday 12th December onwards whereas the observations suggest conditions were dry. During Wednesday 14th and Thursday 15th December the UM predicted less cloud than was observed at both Heathrow and Northolt.

Upper air radiosonde observations from Herstmonceux at 00Z and 12Z from Sunday 11th to Wednesday 14th December are shown in Figure A.5. Temperature and dewpoint profiles are plotted against pressure (in hPa). Dry adiabat lines in which potential temperature is constant with height are shown in green. A smaller decrease of temperature with height than that of the dry adiabats denotes a stable atmosphere. An increase of temperature with height (a temperature inversion) denotes a strongly stable layer. At 00Z on Sunday 11th December there was a strongly stable moist layer near the ground. Above this layer a near neutral layer was present up to about 980 hPa and at higher levels the atmosphere was stably stratified. At 12Z on Sunday 11th December the atmosphere was stably stratified throughout. There was no strong temperature inversion and hence it is difficult to diagnose the depth of the boundary layer from the radiosonde ascent alone. The stable atmosphere would have suppressed mixing of the Buncefield plume by ambient turbulence and the heat of the plume coupled with a very weak temperature inversion enabled the plume to easily punch through the boundary layer top into the free atmosphere aloft. Wind observation vectors

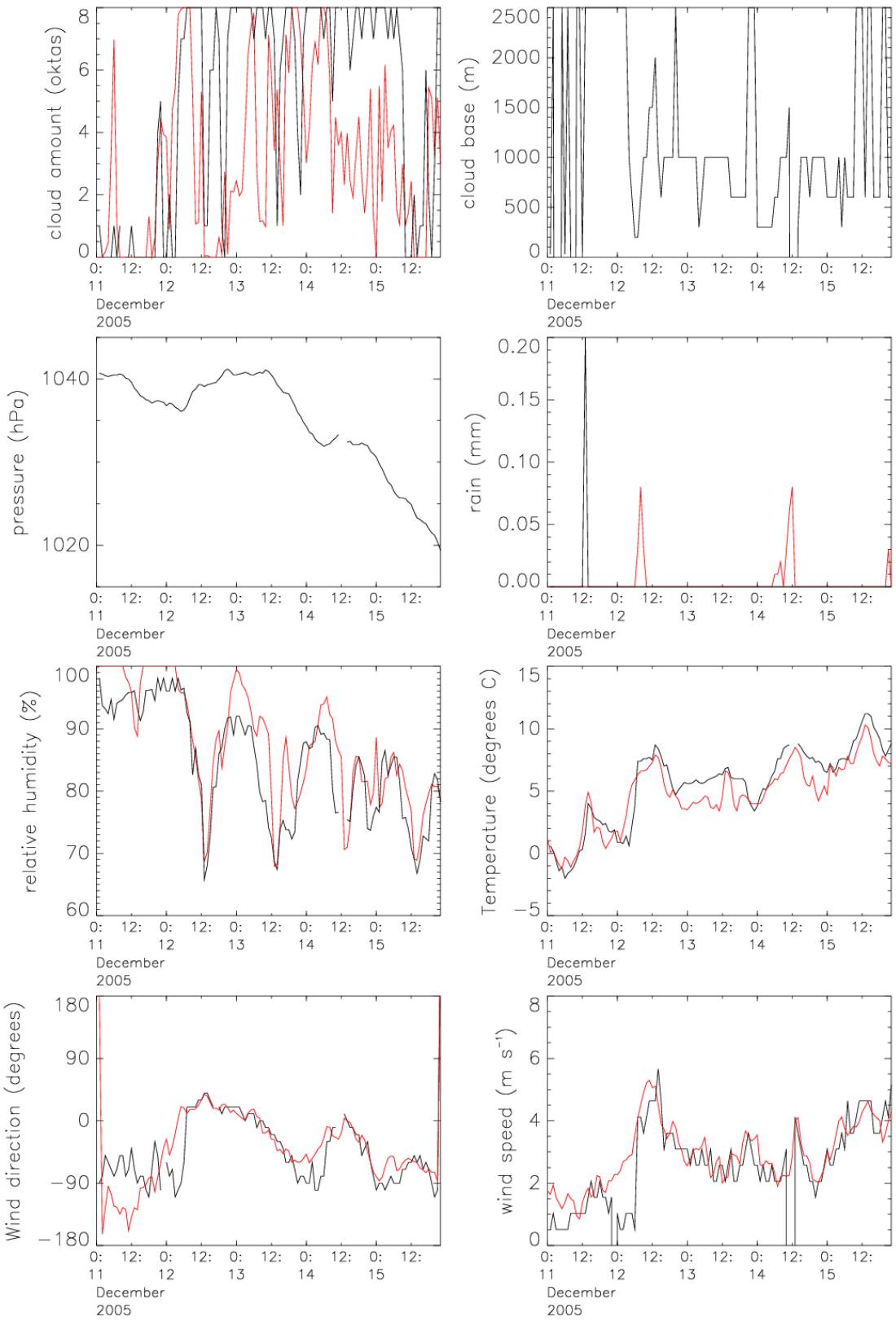

Figure A.2: Comparison of observed (black) and UM (red) meteorology at Heathrow from 11th – 15th December 2005

from the upper air ascents confirm that winds were light and that there was significant wind shear on Sunday 11th December. The temperature profiles from the radiosonde ascents on Monday 12th December show a similar stable

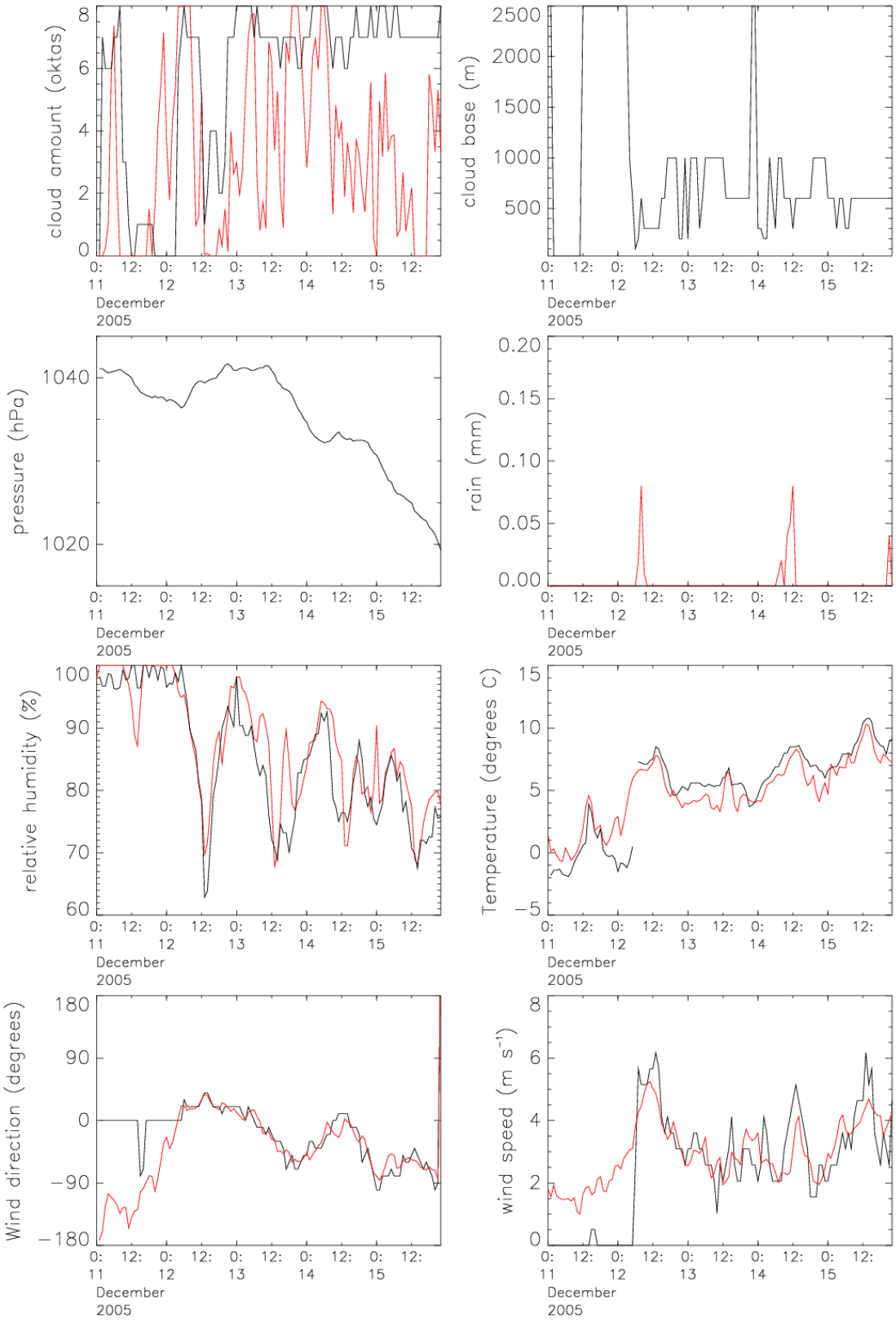

Figure A.3: Comparison of observed (black) and UM (red) meteorology at Northolt from 11th – 15th December 2005

to neutral atmospheric profile with no significant temperature inversion to denote the boundary layer top. However winds were stronger and the wind shear observed on Sunday was not present. On Tuesday 13th December the

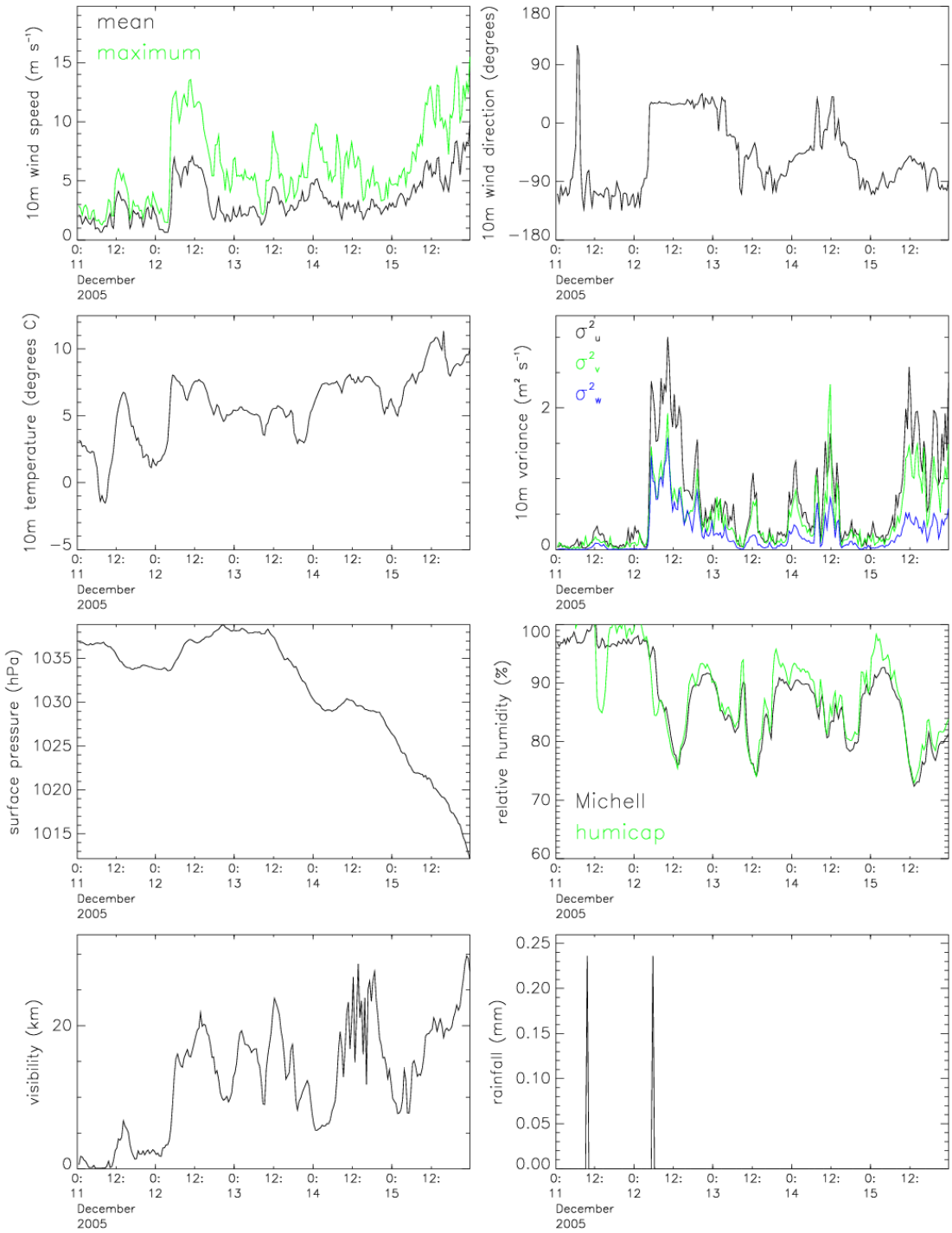

Figure A.4: Observed 30 minute mean meteorology at Cardington at a height of 10m

boundary layer was neutral to stable. A moist layer at around 900 hPa denotes cloud and a temperature inversion at around 875 hPa with an overlying dry stable layer highlights the top of the boundary layer. The stable to neutral atmosphere continued into Wednesday 14th December. The boundary layer top is evident in the temperature profile from the 12Z radiosonde ascent on this day. A moist cloudy layer exists at 850 hPa with a temperature inversion and an overlying dry stable layer at 825 hPa.

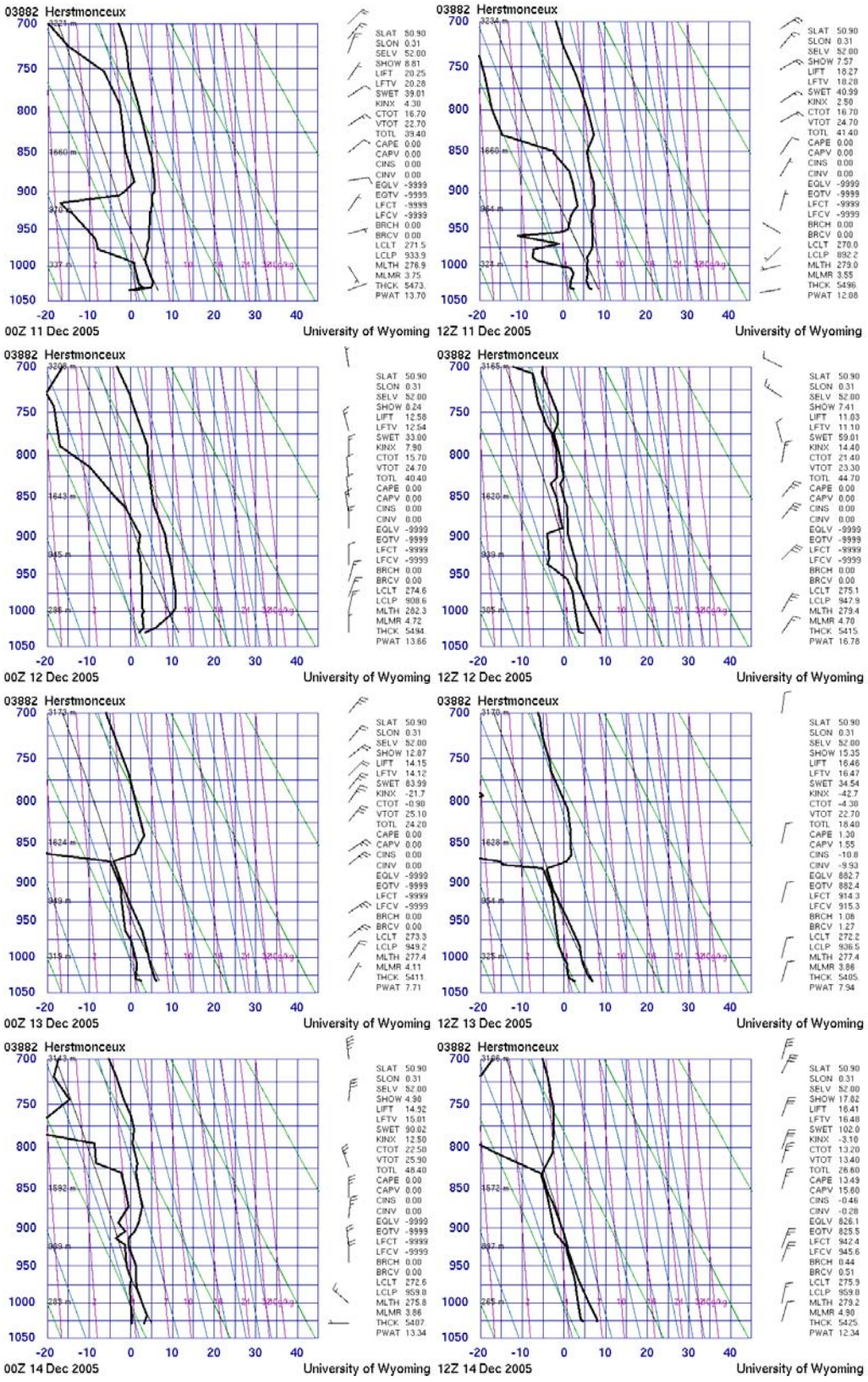

Figure A.5: Upper air radiosonde ascents[6] from Herstmonceux at 00Z and 12Z from 11/12/05 to 14/12/05 showing temperature (right hand curve) and dewpoint profiles (left hand curve) and wind observation vectors

[6] http://weather.uwyo.edu/upperair/sounding.html

Appendix B

B1 FAAM aircraft data

Figures B.1 to B.8 show a selection of aircraft measurements taken on Tuesday 13th December from within the plume both downwind of the source (Figures B.1 to B.5) and directly overhead Buncefield (Figures B.6 to B.8). The position of the aircraft for each run is highlighted in red on the flight track map and the height of the run (mean and standard deviation) is given in metres above ground level. Particle counts measured by the PCASP instrument are shown together with cloud liquid water content (LWC) as the PCASP cannot measure aerosol particles accurately in cloud. The distance travelled by the aircraft on the time series plots is estimated from the measured true air speed. Horizontal and vertical wind components are also shown in addition to measurements of CO, O_3 and NO_x. The increase in CO concentrations within the plume is typical of pollution from combustion sources.

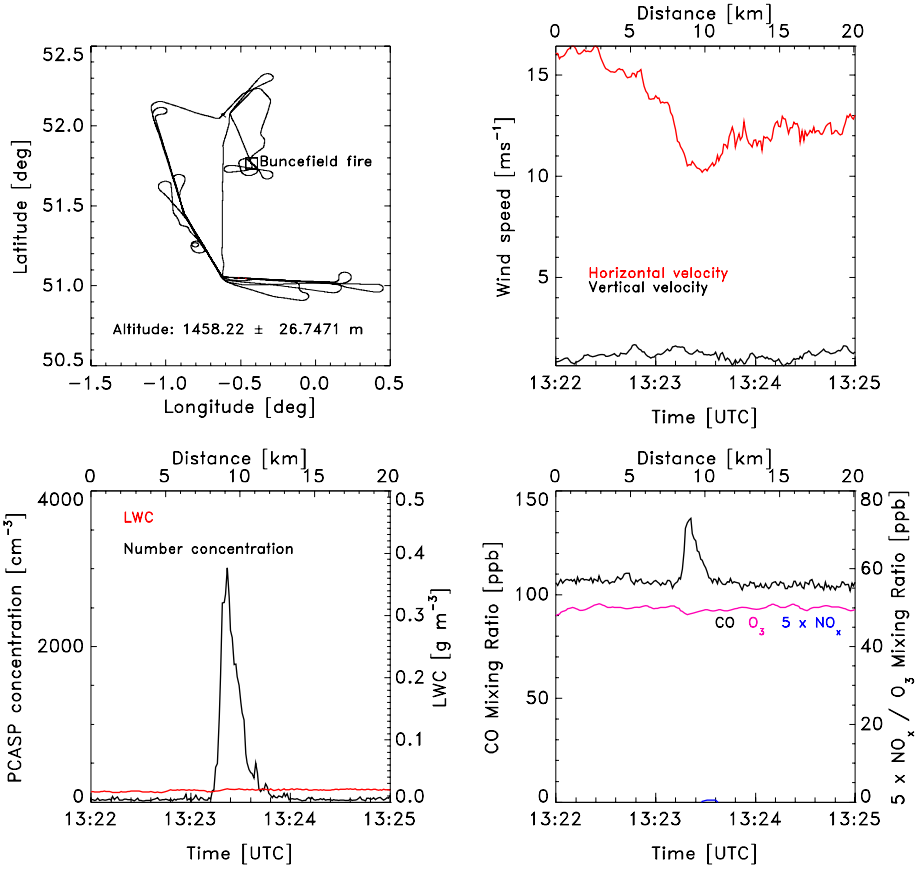

Figure B.1: Aircraft measurements within the plume from run 3 (~78 km downwind of the fire)

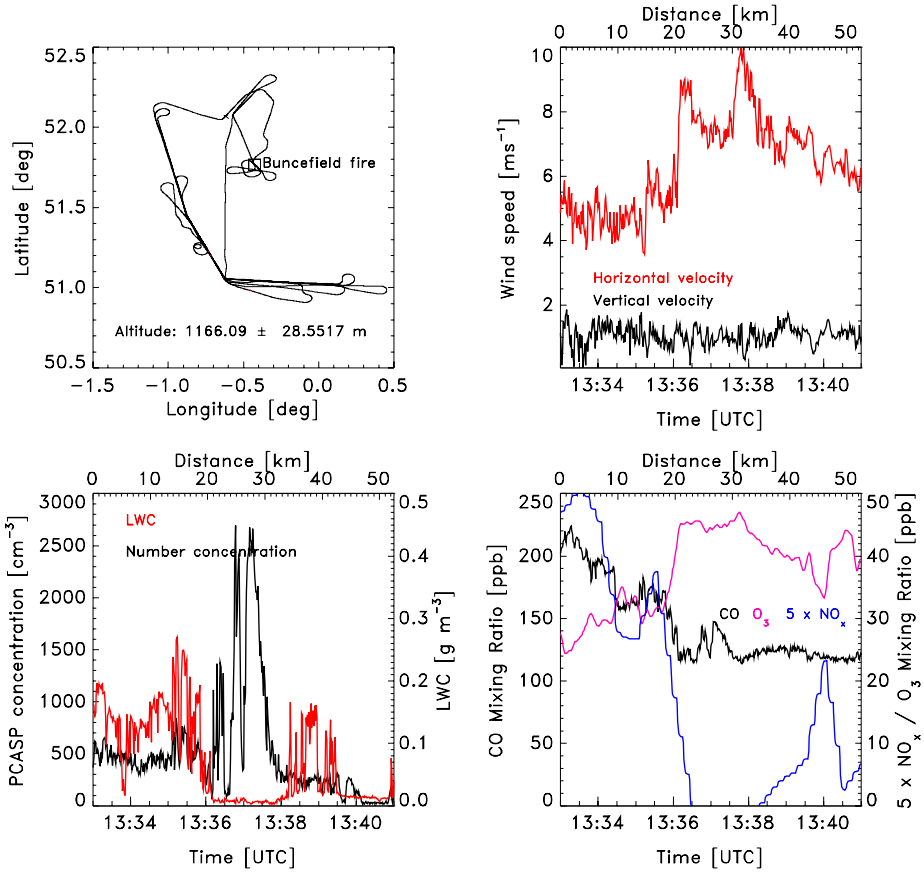

Figure B.2: Aircraft measurements within the plume from run 4 (~78 km downwind of the fire)

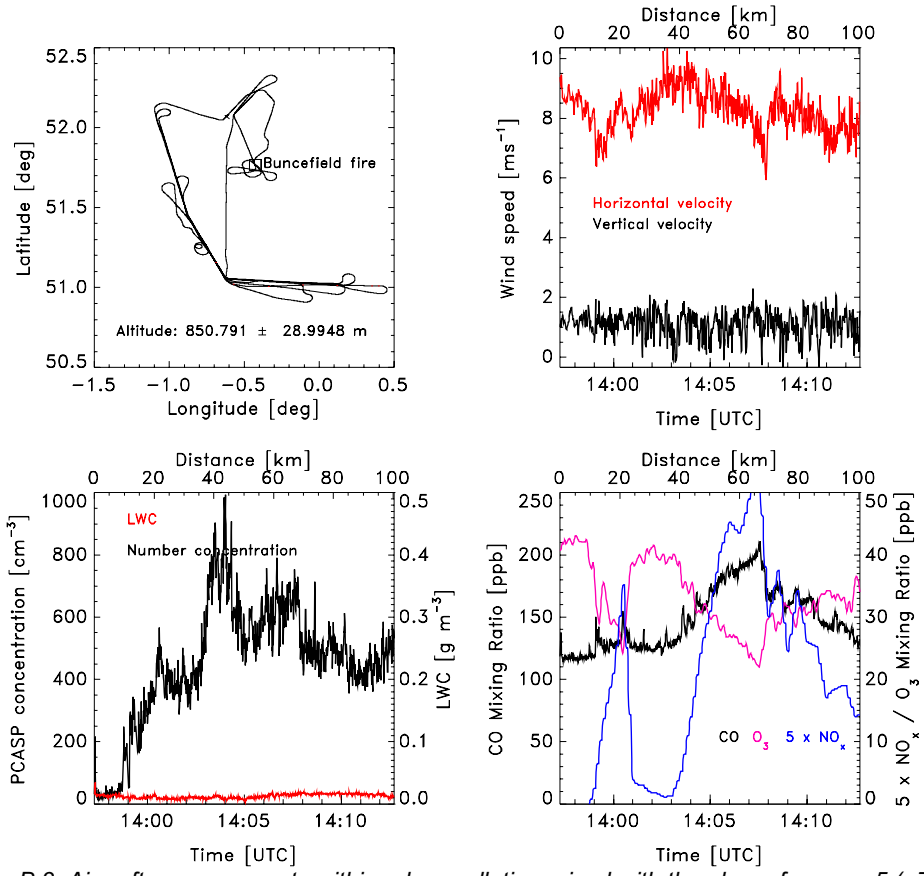

Figure B.3: Aircraft measurements within urban pollution mixed with the plume from run 5 (~78 km downwind of the fire)

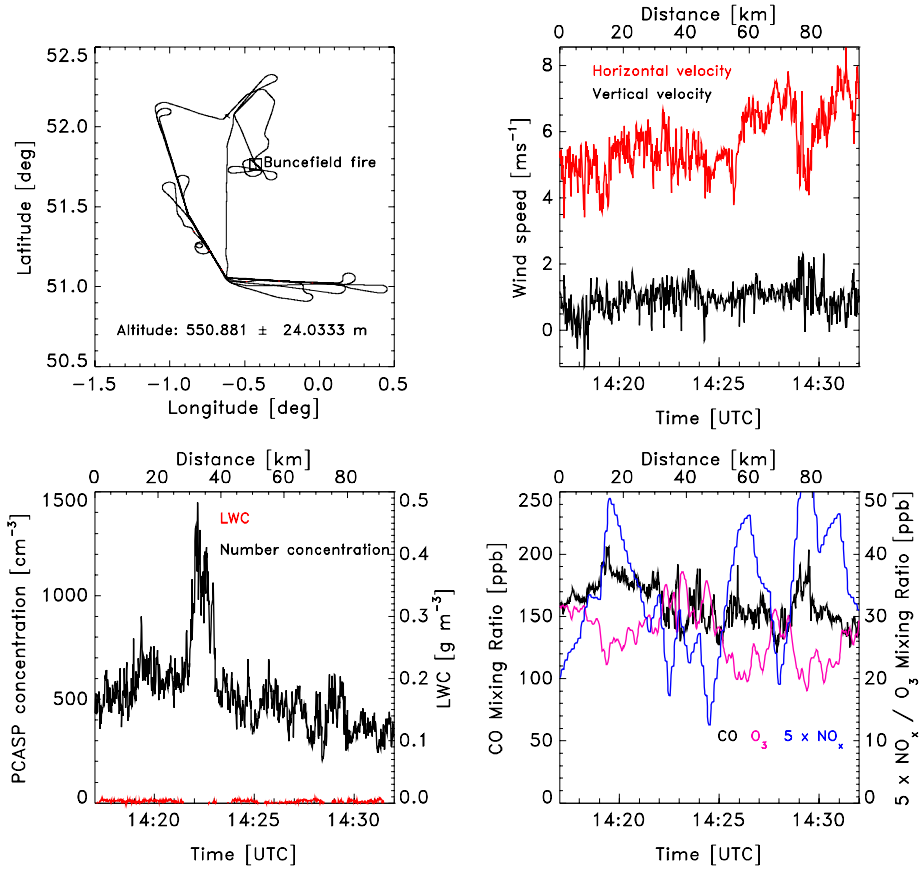

Figure B.4: Aircraft measurements in the boundary layer from run 6 (~78 km downwind of the fire). Possible intersection of the plume at ~ 14:22 UTC

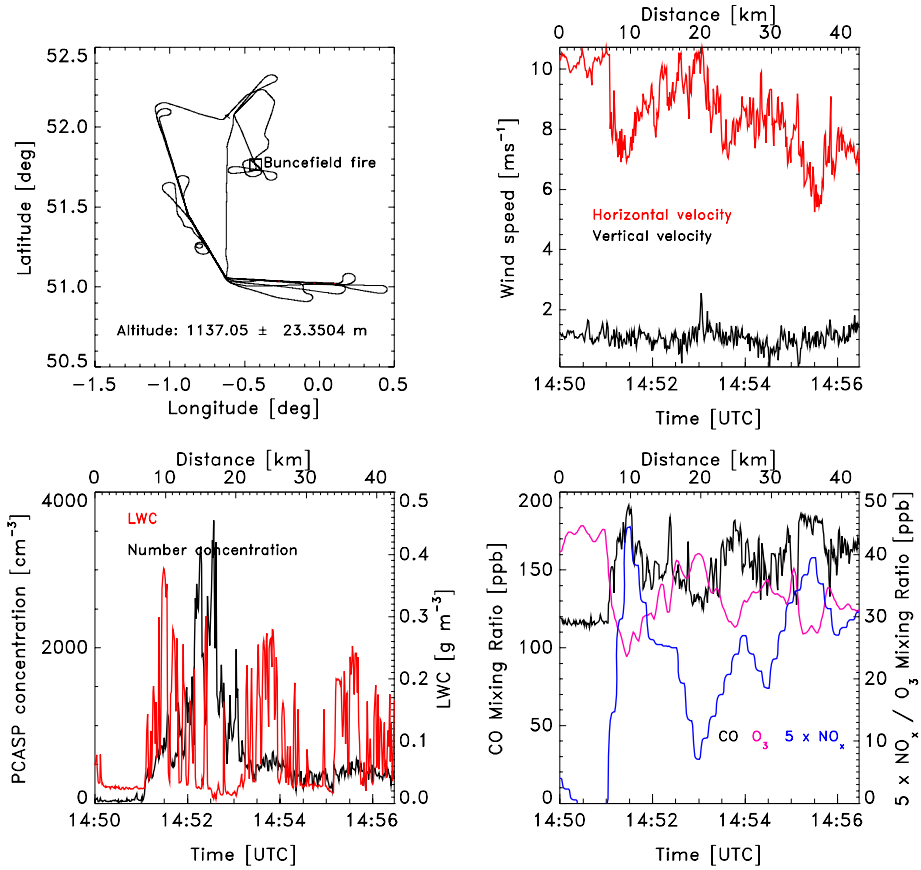

Figure B.5: Aircraft measurements within the plume from run 7 (~78 km downwind of the fire)

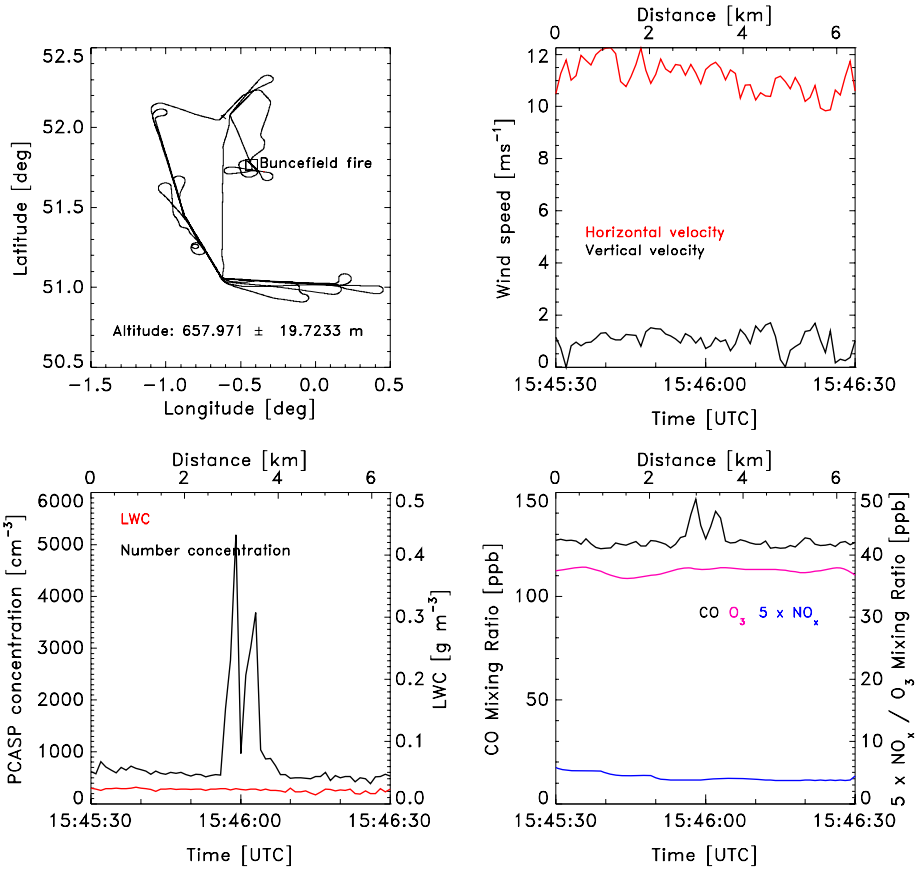

Figure B.6: Aircraft measurements within the plume from run 12 (directly over the source)

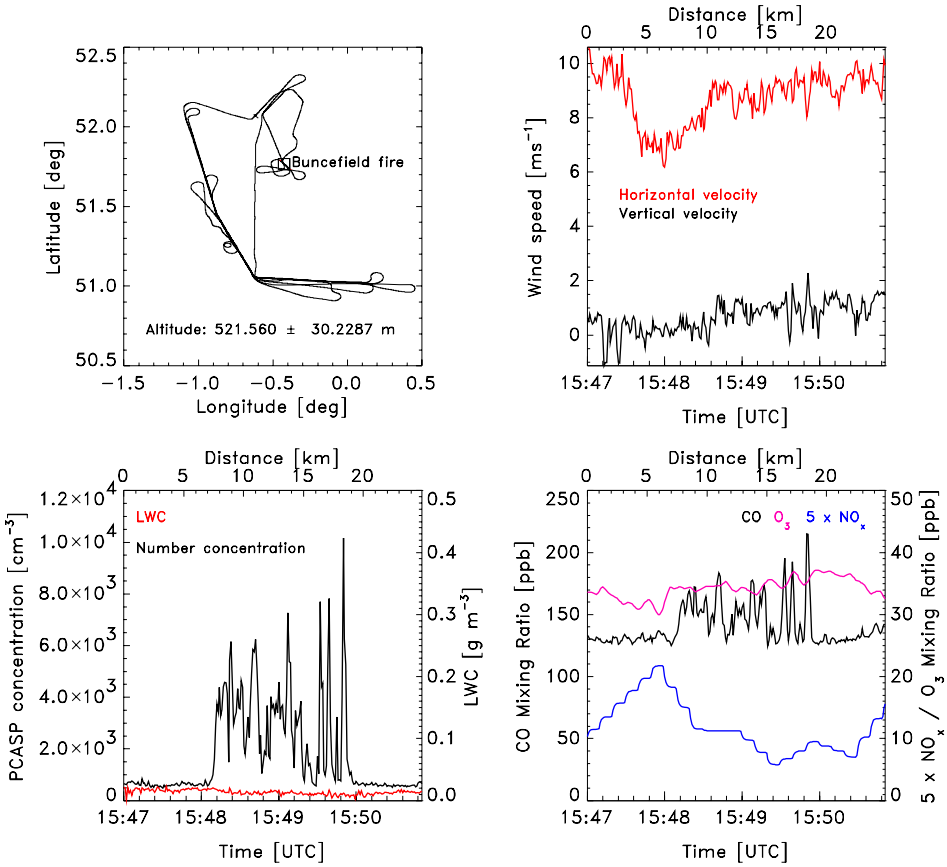

Figure B.7: Aircraft measurements within the plume from run 13 (directly over the source)

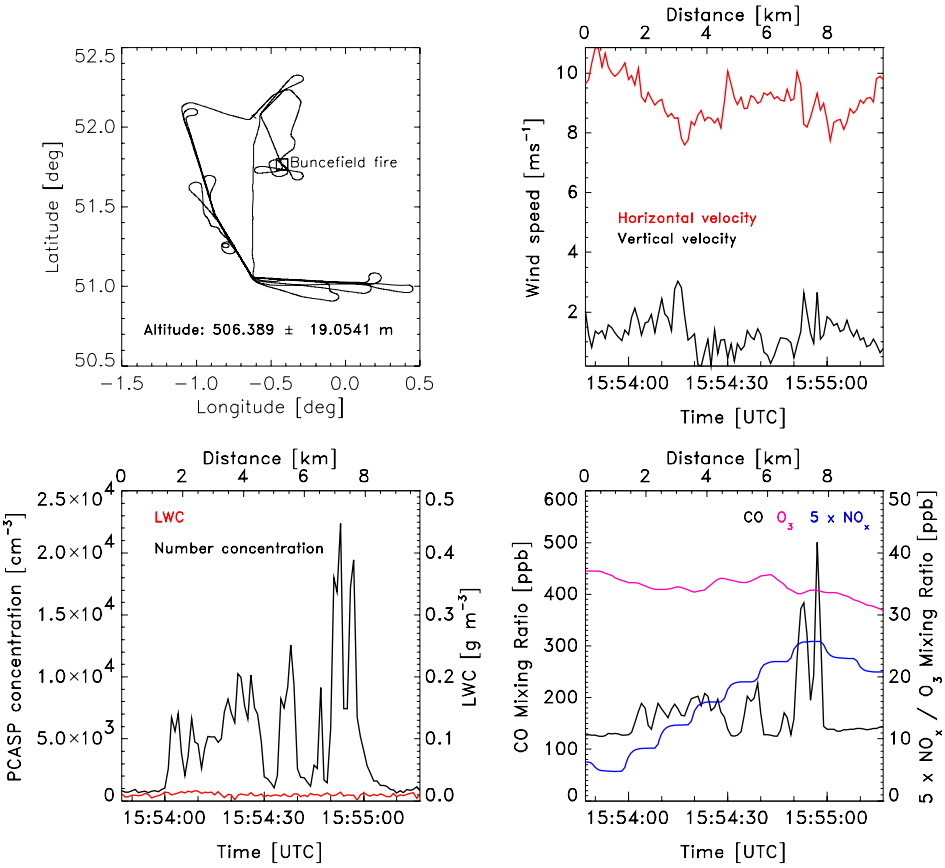

Figure B.8: Aircraft measurements within the plume from run 14 (directly over the source)