FINAL REPORT

UK Air Quality Forecasting:

A UK Particulate Episode from 24th March to 2nd April 2007

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

AEAT/ENV/R/2566 Issue 1, January 2008

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Executive Summary

Over the period Saturday 24th March to Sunday 2nd April 2007 fifty nine sites in the UK Automatic Urban and Rural monitoring network (AURN) measured levels of PM_{10} particulate matter in the MODERATE band (index 4-6), and twenty one of these sites also went on to record HIGH pollution at index 7 or more.

The cause of this PM_{10} particulate episode was likely to have been agricultural fires in the Ukraine and western Russia, possibly combined with some secondary particulate pollution associated with the easterly air trajectories from Europe and long range transport of sand from dust storms over northern Africa (Libya and Egypt) and the Jordan / Syria region.

A number of the sites measured MODERATE or HIGH levels as a result of local pollution sources combined with the additional long-range transport component. However, of the sites measuring PM_{10} air pollution in the MODERATE or HIGH bands, we believe that fifty-seven of these were predominantly due to the particulates transported to the UK on the easterly air currents.

On this occasion the AEA air quality forecasting team did not initially predict the potential of the smoke from the Ukraine/Russian fires and sand storms over northern Africa to affect the UK. No indication of the fires was issued on NASA's "Natural Hazards" website leading up to, during or after the event. This is the forecasting team's primary source of information for global dust and smoke events.

An image of the dust storm in northern Africa, which occurred on the 20th March, was posted on the "Natural Hazards" website late on the Friday leading up to the start of the event on the Saturday. Significant long-range transport of dust from that region of the world to the UK is a rare event due to the need for a large dust storm and suitable meteorology to coincide.

On Monday 26th March an email from the duty forecaster alerted Defra, the Devolved Administrations and other UK air quality experts to the situation. Due to initial uncertainties in identifying the source of the particulates, the episode was not expected to continue after wet weather/ clean Atlantic air had reached many parts of the UK on Thursday 29th March and local particulate levels had dropped in the majority of regions. However, a daily maximum of 21 sites entered the MODERATE band on subsequent days during which time the fires were identified by reviewing further satellite imagery.

Detailed analyses have been carried out by AEA and the Met Office to determine the source, magnitude and extent of this pollution incident.

Contents

1 Introduction

Within this paper we will attempt to:

- Quantify the magnitude and extent of the episode by analysing automatic air pollution monitoring data.
- Identify the source of the pollution by examining:
    - Simple air mass back-trajectory analyses available to the forecasters in real-time during the event,
    - More sophisticated NAME model runs carried out as the episode progressed and subsequently,
    - Ratios of coarse/ fine particulate fractions during the episode.
- Track and understand how the pollution spread across the UK by examination of satellite images over the period of interest and monitoring data from other countries.
- Examine the results from TEOM FDMS PM_{10} monitors compared to traditional TEOMs.

2 Monitoring results

Table 1 attempts to quantify the magnitude of the episode in terms of air pollution index values (see Appendix) recorded in all the affected regions on each day. To keep the table reasonably compact two of the best illustrative sites for twelve roughly divided UK regions have been chosen.

Figures 2a and 2b show hourly-averaged PM_{10} measurements from a small selection of monitoring sites in England, Scotland, Northern Ireland and Wales.

Site name	Site type	Site location	Maximum Air Pollution Index on each day										
			Sat 24th	Sun 25th	Mon 26th	Tues 27th	Weds 28th	Thurs 29th	Fri 30th	Sat 31st	Su 1st Apr	Mon 2nd	Tue 3rd
Norwich Centre	Urban cen	Eastern	-	5	4	-	-	-	-	-	-	-	-
Thurrock	Urban bac	Eastern	-	5	5	5	5	5	-	-	-	-	-
Portsmouth	Urban bac	South	-	8	7	-	4	4	-	-	-	-	-
Southampton Cen	Urban cen	South	-	7	7	-	-	-	-	-	-	-	-
Reading T Cen	Urban bac	South east	-	5	5	6	6	7	4	6	4	4	-
Harwell	Rural	South east	-	6	5	-	4	-	-	-	-	-	-
Bloomsbury	Urban cen	London	-	7	6	5	5	5	-	4	-	4	4
North Kensington	Urban bac	London	-	6	5	5	5	5	-	-	-	-	-
Plymouth Centre	Urban cen	South west	-	6	6	-	5	5	-	4	-	-	-
Bristol St Paul's	Urban bac	South west	-	-	-	5	8	7	-	5	-	-	-
Birmingham Cen	Urban cen	Midlands	-	5	5	7	8	7	5	6	-	-	-
Coventry M Park	Urban bac	Midlands	-	5	5	6	7	7	5	6	-	-	-
Narbeth	Remote	S Wales	-	6	7	-	-	-	-	-	-	-	-
Cardiff Centre	Urban cen	S Wales	-	5	5	6	7	6	-	6	4	-	-
Wirral Tranmere	Urban bac	(N Wales)[+]	-	5	5	4	4	-	-	-	-	-	-
Stockton on Tees*	Roadside	North east	-	4	6	7	7	6	5	5	-	-	-
Newcastle Centre	Urban cen	North east	-	-	-	4	5	5	5	5	-	-	-
Stockport S Heath	Urban bac	North west	-	5	5	4	5	4	-	-	-	-	-
Manchester P	Urban cen	North west	-	5	5	7	9	8	5	5	-	-	-
Glasgow Centre	Urban cen	Scotland	-	-	-	4	5	-	-	-	-	-	-
Glasgow Kerb *	Kerbside	Scotland	5	4	6	7	7	-	7	6	-	-	-
Belfast Centre	Urban cen	N Ireland	-	-	-	5	6	-	-	-	-	-	-
Lough Navar	Remote	N Ireland	-	-	-	-	-	-	-	-	-	-	-

Table 1: The March 2007 particulate episode quantified

* indicates sites where possible significant local pollution contributed to the levels measured during the episode.

Index levels in the HIGH band are highlighted in red. Index levels in the MODERATE band are highlighted in blue. "-" indicates where levels remained in the LOW band.

[+] the Wirral Tranmere site has been used as a proxy to represent North Wales due to a limitation in the number of AURN particulate instruments in that region.

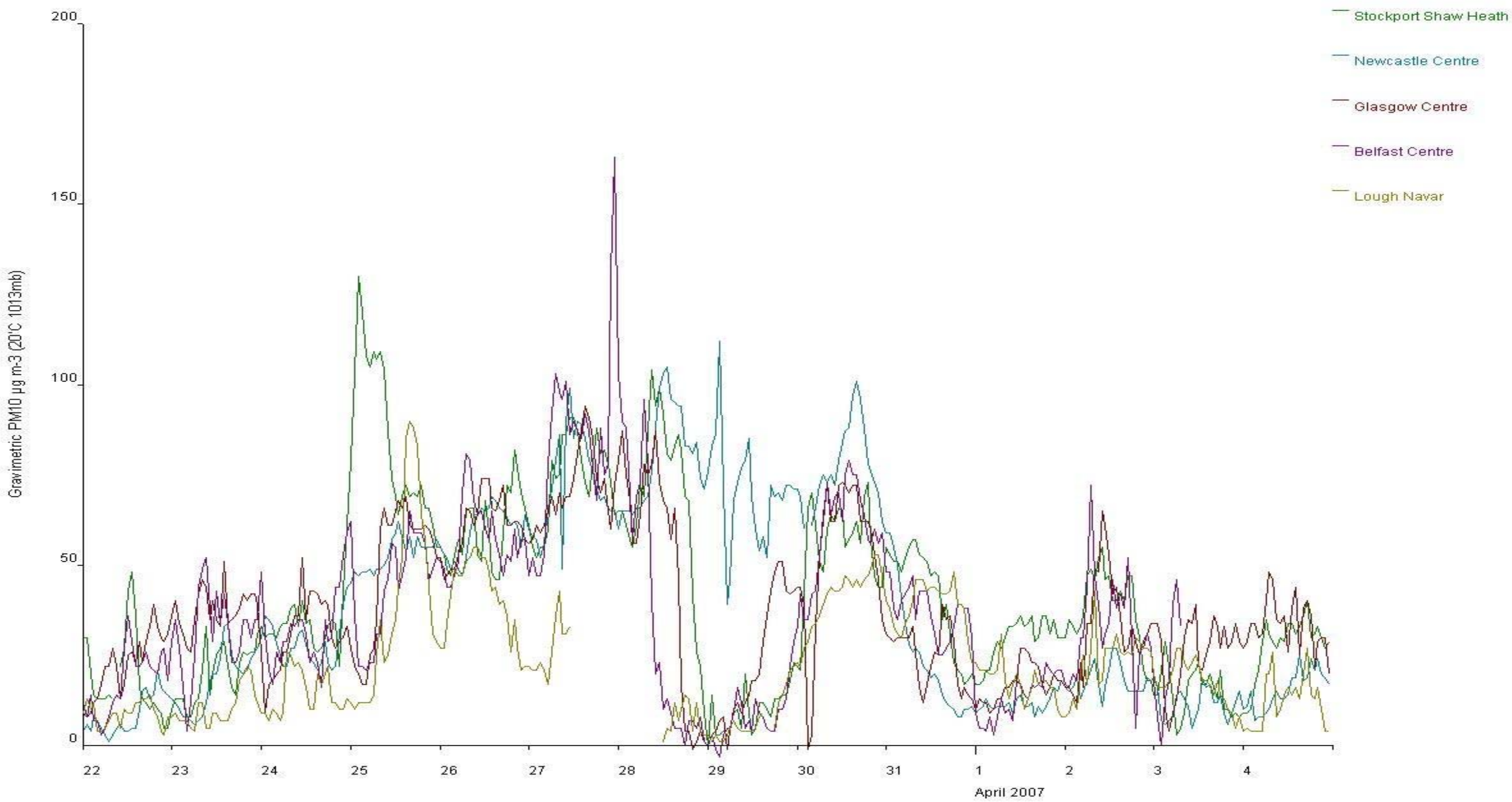


Figure 2a: Hourly mean PM_{10} (TEOM x1.3, gravimetric equivalent) measurements at selected northern sites in the UK for March 22nd to 4th April

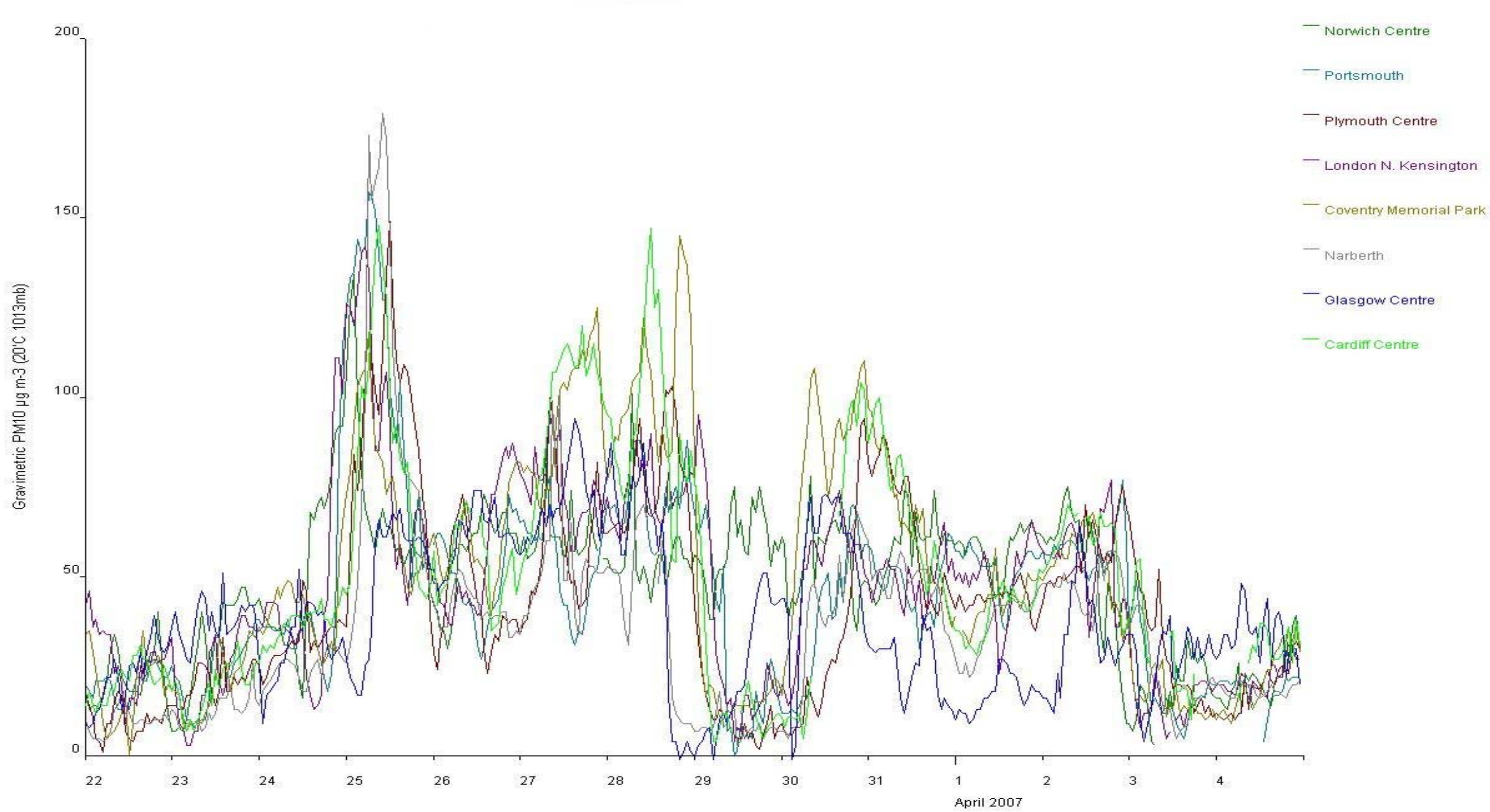


Figure 2b: Hourly mean PM_{10} (TEOM x1.3, gravimetric equivalent) measurements at selected southern sites (with Glasgow for comparison) for March 22nd to 4th April

Figure 2c shows the responses from the TEOM $PM_{2.5}$ and PM_{10} instruments at London Bloomsbury during the episode. A predominance of the coarse particulate fraction was noticed by the AEA forecasting team during the infancy of the episode. Figure 2d shows the relative ratio contribution of $PM_{2.5}$ and PM_{coarse} calculated using daily averaged data from London Bloomsbury. This figure clearly shows that as the episode progressed the particulate fraction measured became finer up to the 30th March then progressively coarser to the end of the episode (although by April 3rd concentrations had returned to a level more commonly associated with ambient background). It is acknowledged that the day of rain or clean Atlantic air on the 29th March may have had a temporary effect on the ratios on one or possibly two days. Please note $PM_{coarse} = (PM_{10} - PM_{2.5})$.

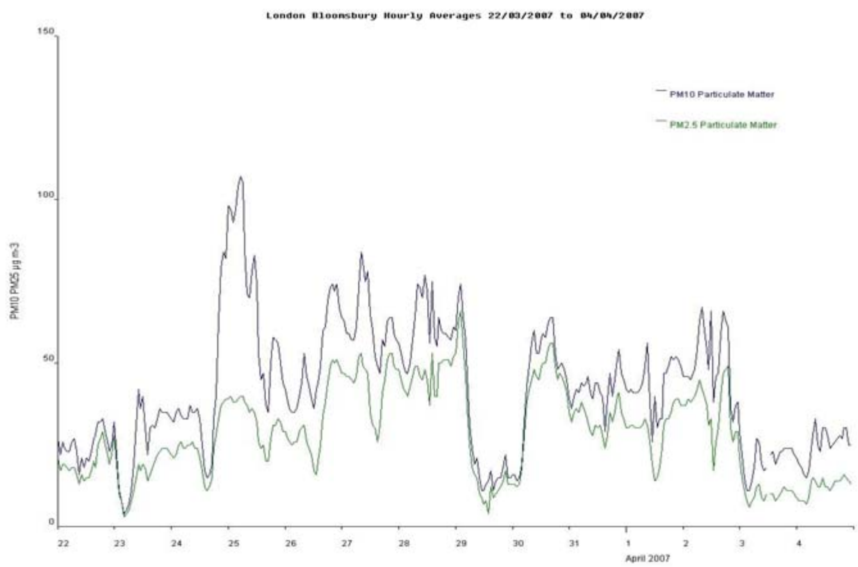


Figure 2c

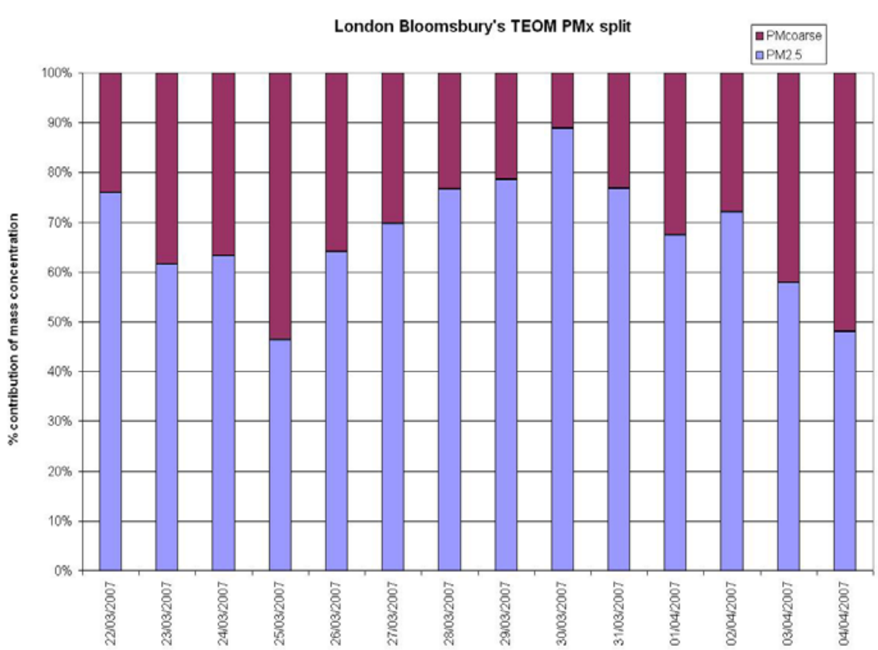
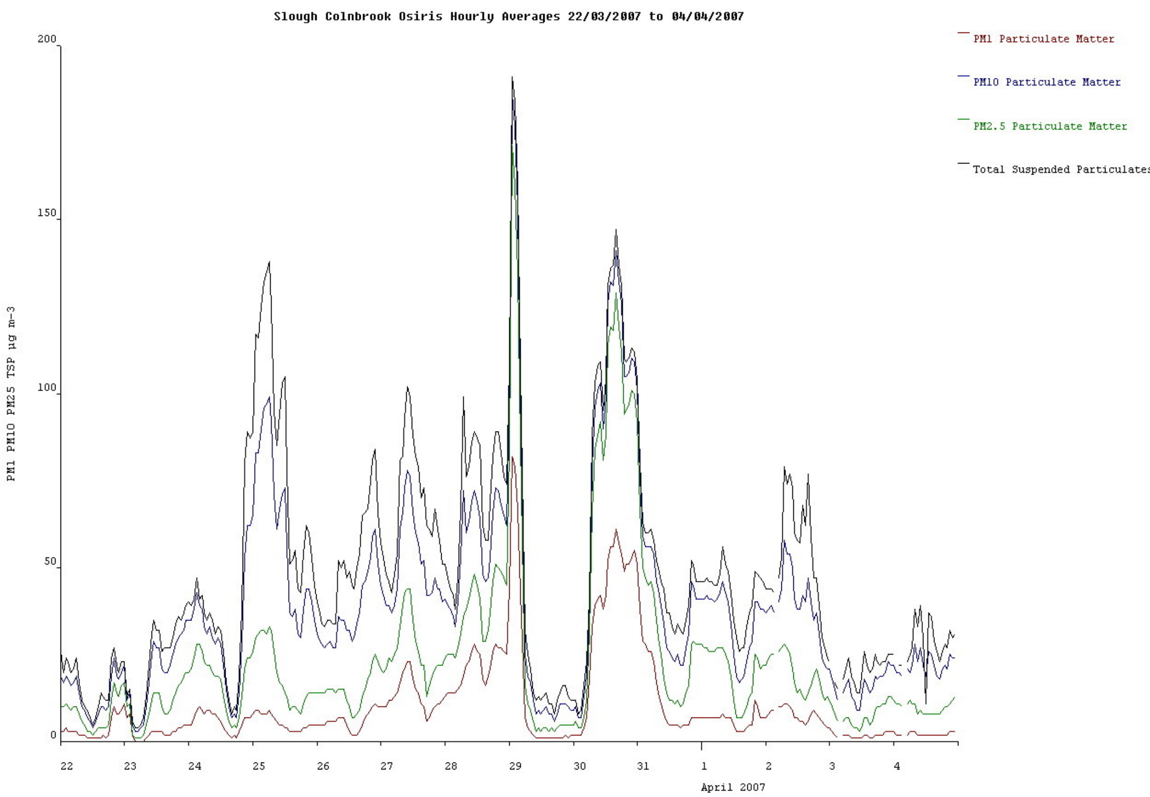


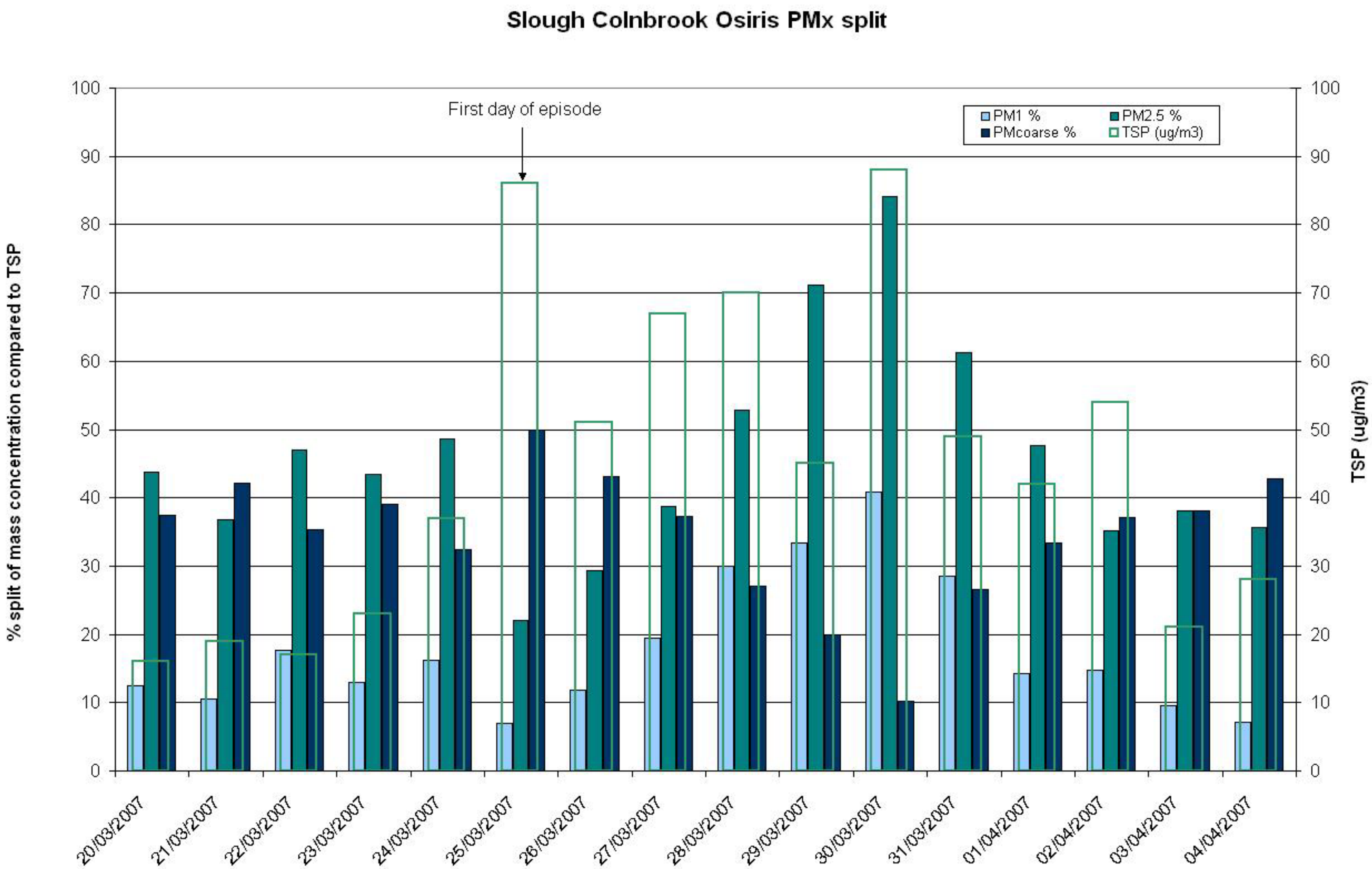
Figure 2d

The Osiris particulate measurement instrument uses an optical laser technique for "indicative" measurements of particulate matter in the UK. The instrument's measurement range is from 0.5 to 20 microns particle diameter. This instrument can monitor PM_1 , $PM_{2.5}$, PM_{10} and total suspended particulates (where TSP = PM_1 to PM_{20}) simultaneously. The Osiris monitor at Slough Colnbrook provided the hourly averages in figure 2e during the course of the episode. These have been used to calculate the percentage contribution ratios from three fractions compared to the total suspended particulates in terms of daily averages, as shown in figure 2f. In this figure the daily TSP mass concentration has been added to illustrate how the episode progressed. Again this shows, albeit in greater detail, the variance in the relative fractions over the episode.



By kind permission of Slough Borough Council

Figure 2e



Slough Colnbrook Osiris PMx split
First day of episode
PM1 %
PM2.5 %
PMcoarse %
TSP (ug/m3)
% split of mass concentration compared to TSP
TSP (ug/m3)
0
10
20
30
40
50
60
70
80
90
100
20/03/2007
21/03/2007
22/03/2007
23/03/2007
24/03/2007
25/03/2007
26/03/2007
27/03/2007
28/03/2007
29/03/2007
30/03/2007
31/03/2007
01/04/2007
02/04/2007
03/04/2007
04/04/2007

Figure 2f

Figure 2g shows the response from the FDMS-TEOM instrument at Coventry Memorial Park over the episode. This type of instrument is able to determine the volatile and non-volatile components of the PM_{10} fraction and operates at a temperature of around 30 degrees C, 20 degrees lower than a standard TEOM. In most circumstances the non-volatile fraction is measured as a greater quantity compared to the volatile component. The two channel responses plotted show that the volatile fraction of the particles collected slowly increased from the 26th onwards and gradually dropped from a maximum peak around the 28th up to the end of the episode. A day of rain or clean air from the west confuses the trend momentarily on the 29th. The trend observed is consistent with air passing across Europe to the UK throughout the working week, with the volatile fraction measured likely to be secondary volatile species within the particles sampled. There is usually a lag time of about one day for the air from continental Europe to reach the UK.

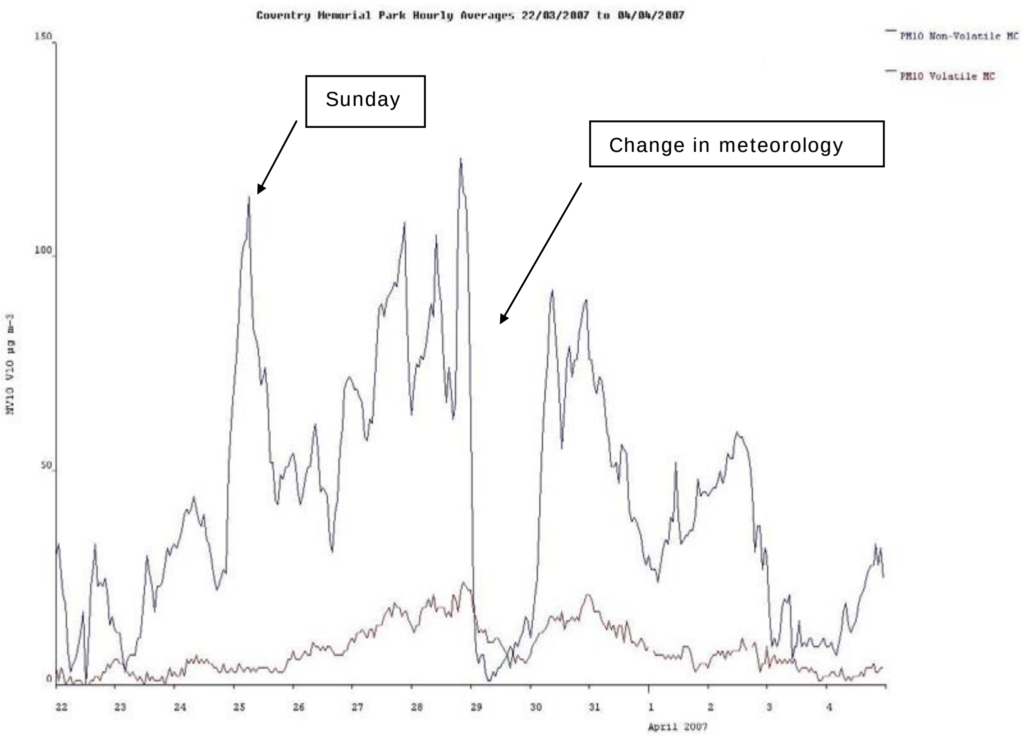


Figure 2g

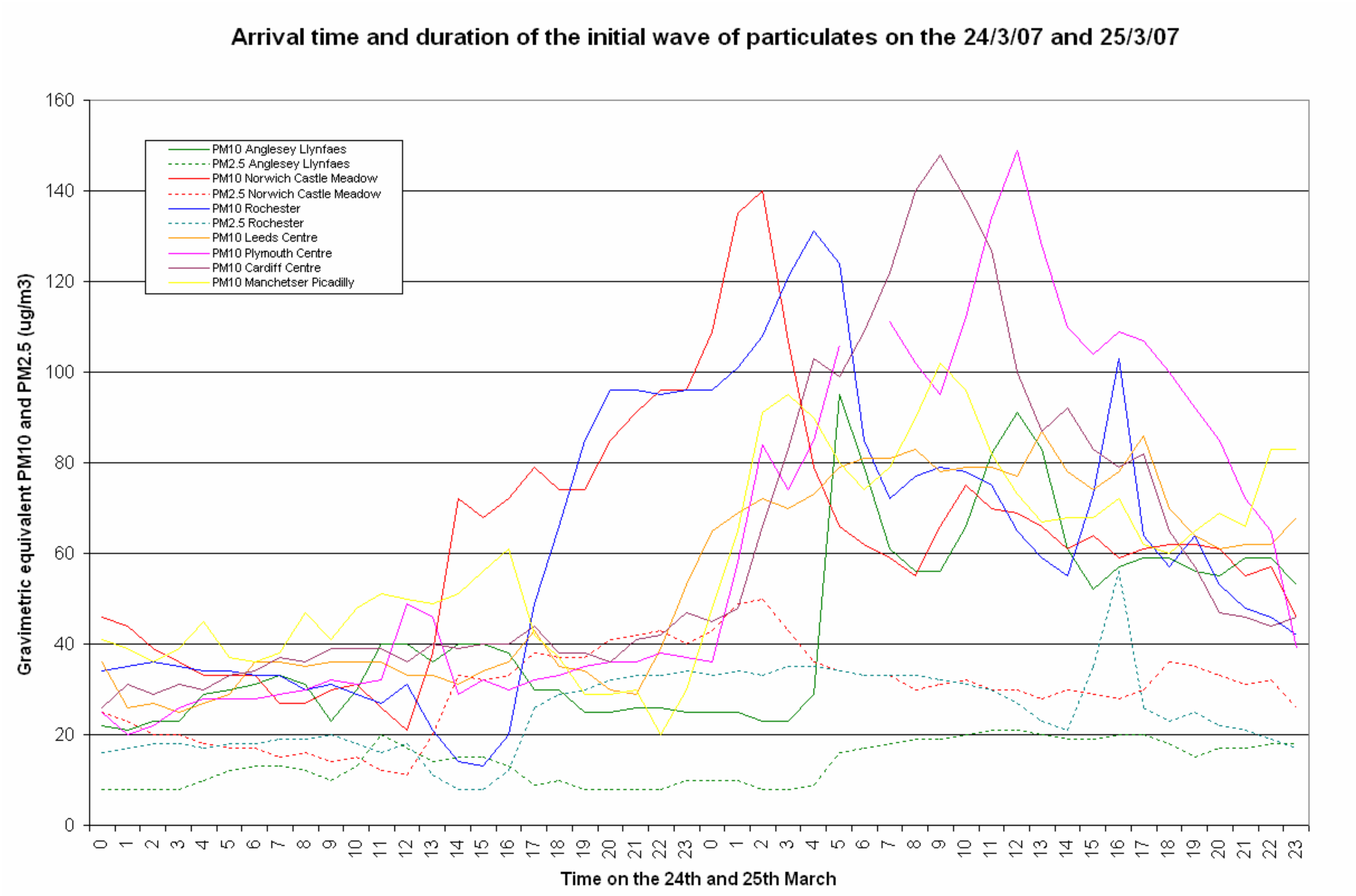
2.1 Characterising the onset of the episode

The initial wave of particulates arrived in Norwich Centre at approximately 2 p.m. on Saturday 24th March and had reached Cardiff Centre by about 3 a.m. on the morning of Sunday 25th. The site at Lough Navar in Northern Ireland measured its first elevated reading at around 2 p.m. on Sunday 25th. Figure 2h shows a comparison plot of PM_{10} measurements made at specific sites in various regions of the UK on the 24th and 25th March with $PM_{2.5}$ measurements added, where these were available. Sites used for the comparison were: Anglesey Llynfaes (non DEFRA network site) in North Wales, Norwich Castle Meadow (also a non DEFRA network site) in East Anglia, Rochester in the south east of England, Plymouth Centre in the south west of England, Cardiff Centre in South Wales, Leeds Centre in the Yorkshire area and Manchester Piccadilly located towards the north west of England.

From figure 2h the following conclusions can be made:

- The particulates arrived in East Anglia during the early afternoon of Saturday 24th March.
- Within about 4 hours of the initial increase in particulates reaching the north east of East Anglia, the episode had spread to the South East of England.
- Within about 12 hours of the arrival time of the particulates in East Anglia the initial episode reached the south west of England, South Wales and the majority of regions in England.
- Most of the initial episode of larger diameter particles passed over the south of the UK (including South Wales). Further analysis indicated that the Midlands and North Wales were affected by the initial episode but only for a short time. Sites in areas to the north of the UK measured the onset but did not measure such significant peaks as those seen towards the south.
- As also seen in other analysis the initial episode of particulates was mainly composed of coarse, larger diameter particles which initially suggested that long range transport of dust from Saharan sandstorms was responsible for the measurements made at the onset of the episode.

Reports made by members of the public to Horsham District Council, in south east England, during the initial phase of the episode indicated that the dust fall in that area was light brown in colour, fine and gritty.



Arrival time and duration of the initial wave of particulates on the 24/3/07 and 25/3/07
PM10 Anglesey Llynfaes
PM2.5 Anglesey Llynfaes
PM10 Norwich Castle Meadow
PM2.5 Norwich Castle Meadow
PM10 Rochester
PM2.5 Rochester
PM10 Leeds Centre
PM10 Plymouth Centre
PM10 Cardiff Centre
PM10 Manchetser Picadilly
Gravimetric equivalent PM10 and PM2.5 (ug/m3)
Time on the 24th and 25th March

Figure 2h

3. Magnitude of the long range transport contribution.

Figures 3a to 3d show the additional daily averaged contributions of gravimetric equivalent particulate PM_{10} above an estimated site background over the period 25th March to the 2nd April at rural or background sites in England (Harwell), Scotland (Aberdeen), Wales (Narberth) and Northern Ireland (Lough Navar). Background levels were estimated on these days using gravimetric equivalent PM_{10} data averaged over the periods: 1st – 23rd March and 4th – 9th April, periods of non-episodic data. Daily averages were obtained for each site for the period 25th March to 2nd April, these were complete days of the episode. Inaccuracies may be seen using this model if localised pollutant contributions occurred during the background estimation period, although these sites were chosen after consideration of the time series plots for the relevant time periods.

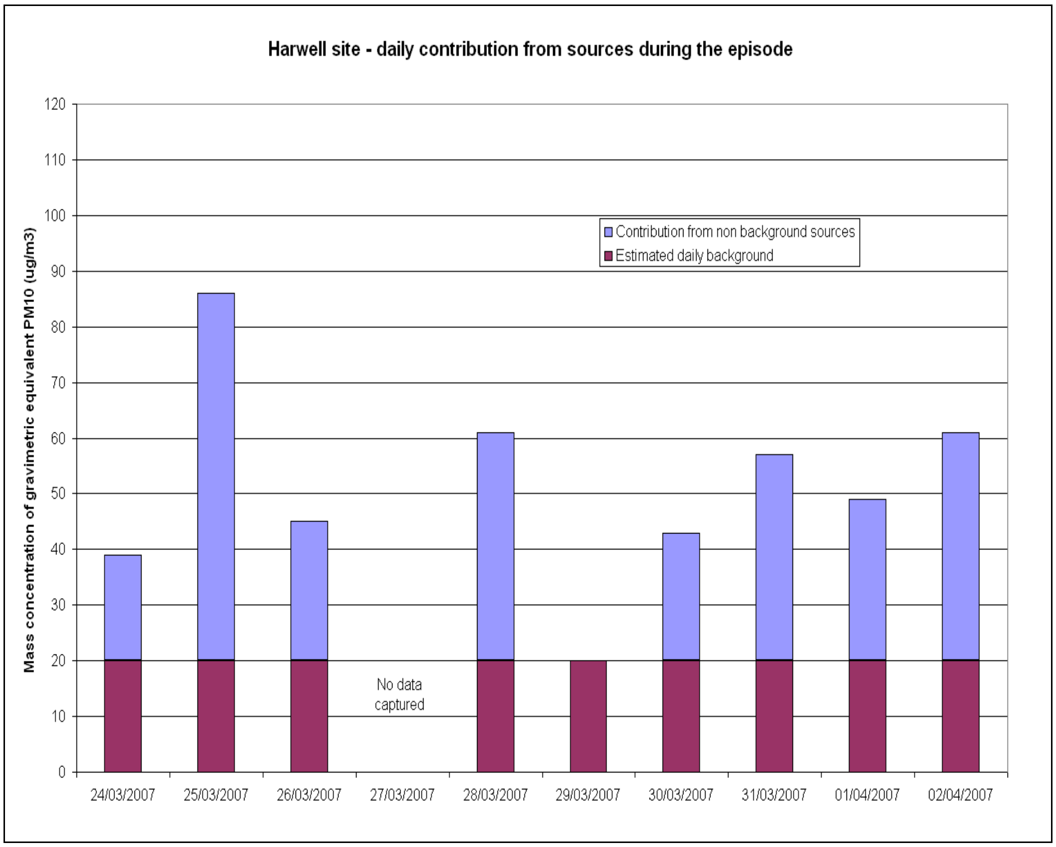


Figure 3a: Estimated additional contributions of particulate PM_{10} at Harwell.

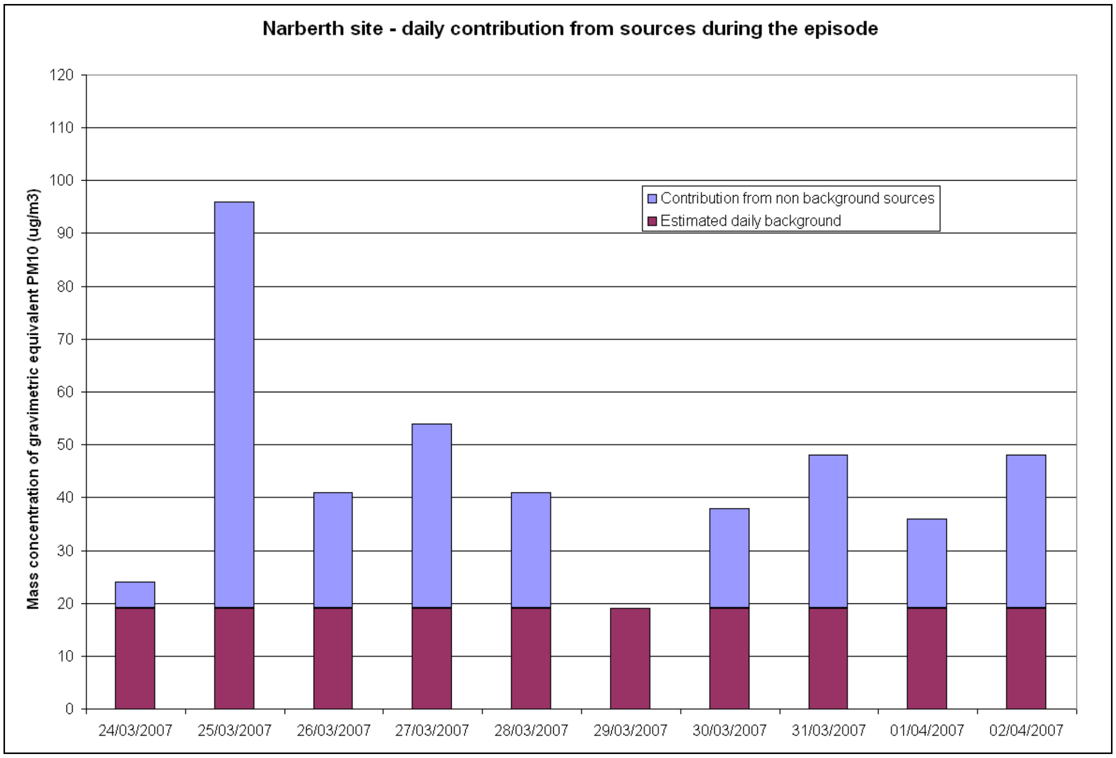


Figure 3b: Estimated additional contributions of particulate PM_{10} at Narberth.

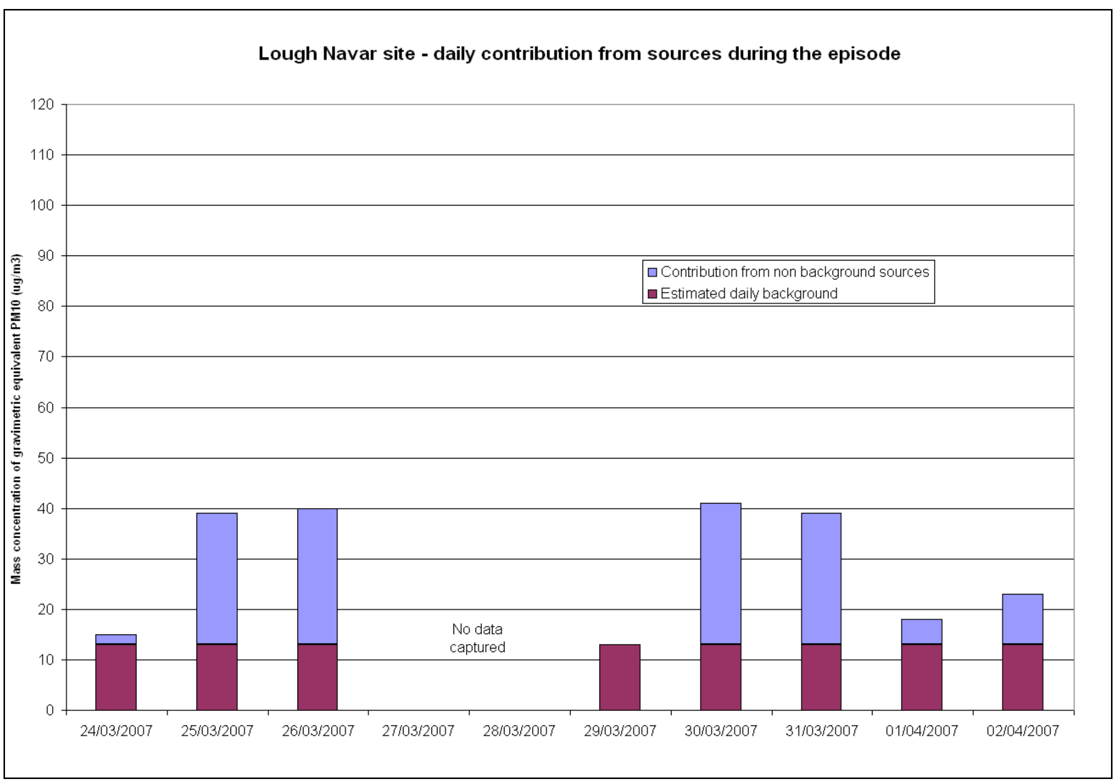


Figure 3c: Estimated additional contributions of particulate PM_{10} at Lough Navar.

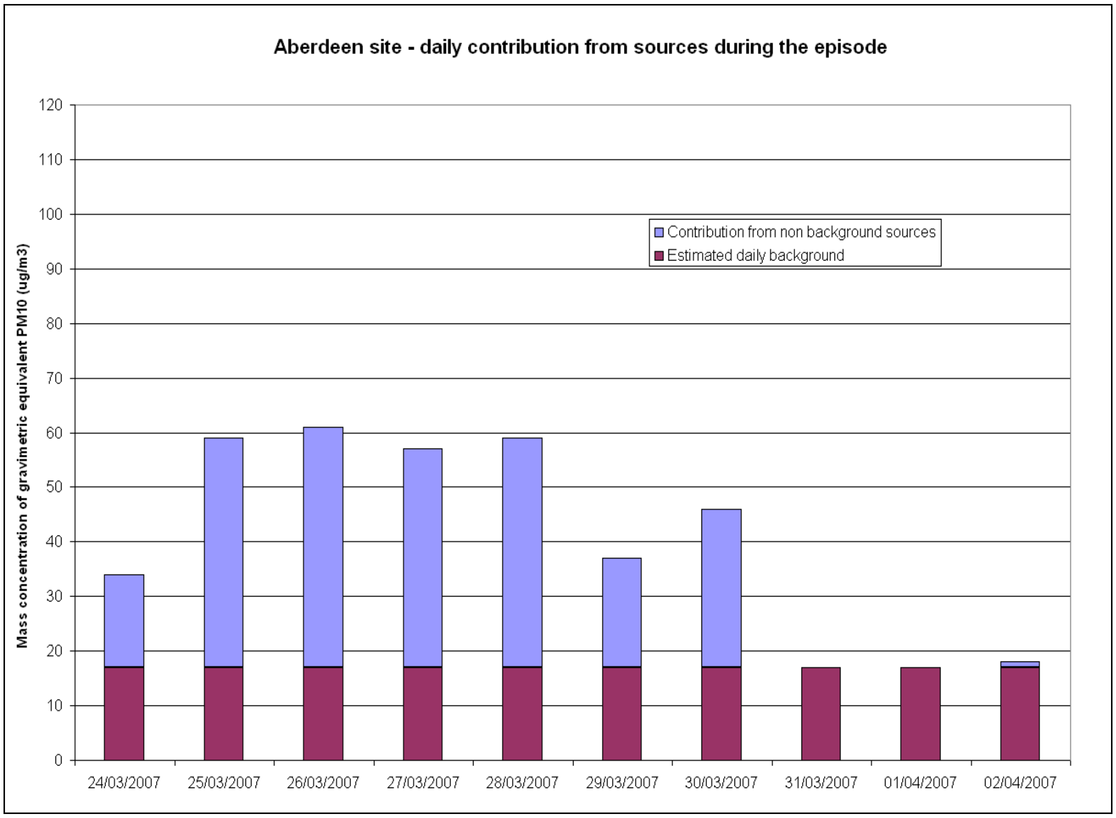


Figure 3d: Estimated additional contributions of particulate PM_{10} at Aberdeen.

Figure 3e shows the estimated additional episode contribution of gravimetric equivalent particulate PM_{10} at specific sites in 13 regions of the UK. Gravimetric PM_{10} data were averaged from 25th March to 2nd April to represent the episode. Background levels were again estimated using gravimetric PM_{10} data averaged over the periods: 1st – 23rd March and 4th – 9th April. Inaccuracies may be seen using this model if localised pollutant contributions occurred during the background estimation period, although these sites were chosen after consideration of the timeseries plots for the relevant time period.

The contribution percentages, as noted in the figure, do not show a clear trend for site designations (e.g. rural or urban etc) but do show contribution ratios of the order of 55 to 75% from long-range transport at the sites chosen. Please note that the remote Lough Navar site is in Northern Ireland which was not significantly affected by the episode. This could explain why the contribution figure for this site is lower than expected.

Local pollutant emission make a much more significant contribution to PM_{10} concentrations at roadside and kerbside locations, so the episode is much harder to detect at these sites and they have not been included in this analysis.

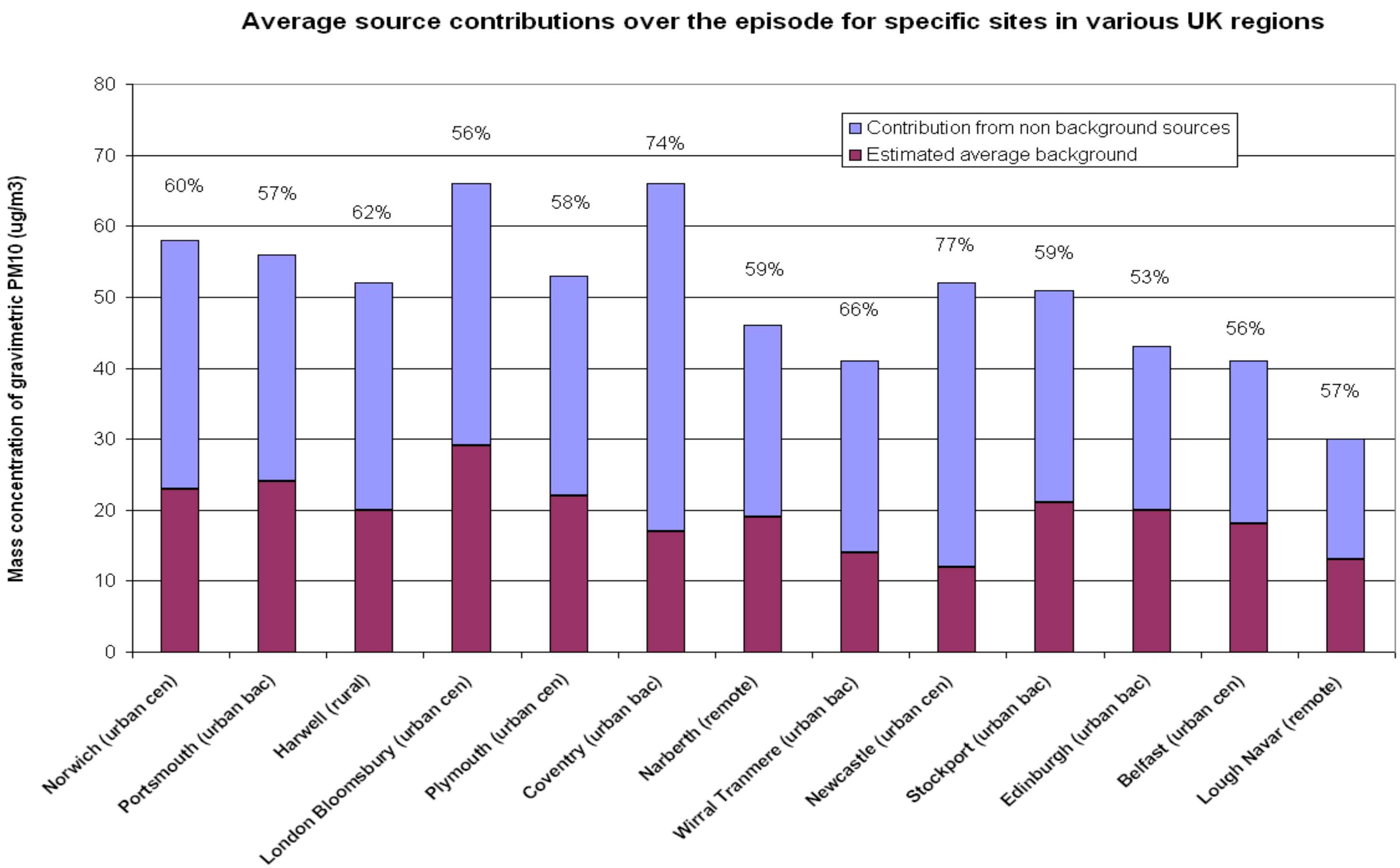


Figure 3e: Estimated average additional contributions of particulate PM_{10} for the whole episode at sites in various UK regions.

4. Air mass back trajectory analysis

Simple 1000mB 96-hour forecast air mass back-trajectory data are provided by the Met Office to the AEA Energy & Environment air pollution forecasting team each day. These data, as shown in figures 4a to 4j, illustrated that the air arriving in the UK up to the 26th March had originated from western Russia and had passed over northern Europe in transit. By the 27th March a warm front had arrived from the west, temporarily bringing Atlantic air to western areas of the UK. Outbreaks of rain over much of the UK on the 28th March saw particulate levels drop rapidly for one day, although any effect on the 24 hour running averages used in the bandings for PM_{10} was minimal. The low pressure had passed away to the south east by the 30th March and high pressure returned. From the end of March onwards low pressure over northern France and Spain encouraged easterly air to pass across most of the UK. Scotland and Northern Ireland were in a cleaner, more northerly air stream. By the 3rd April the air arriving in all areas had been sourced from the Atlantic and particulate levels had dropped back to normal ambient background.

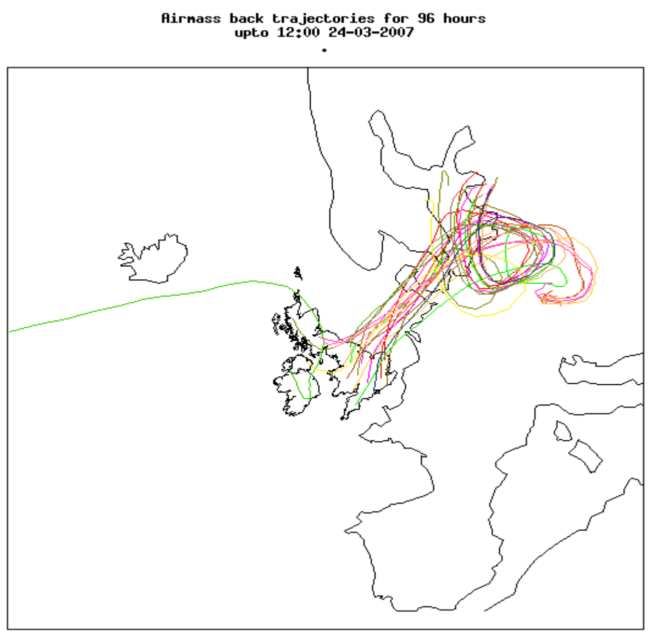


Figure 4a: Air mass back-trajectories for 24th March

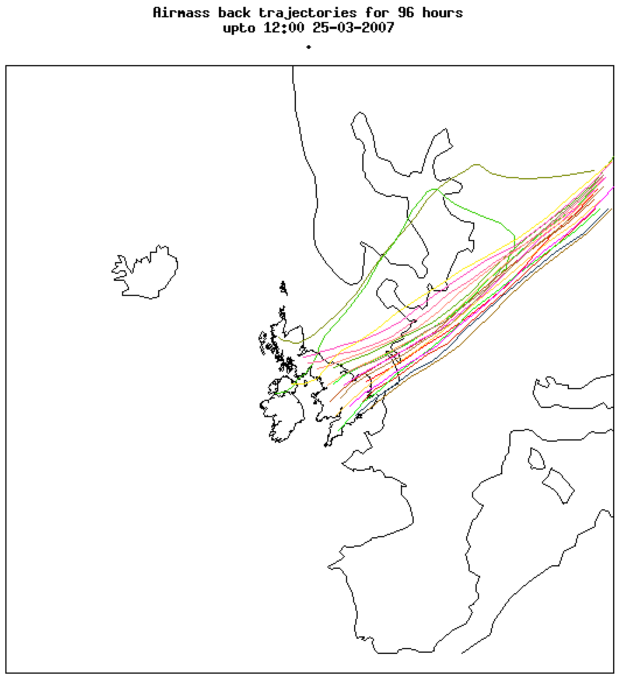


Figure 4b: Air mass back-trajectories for 25th March

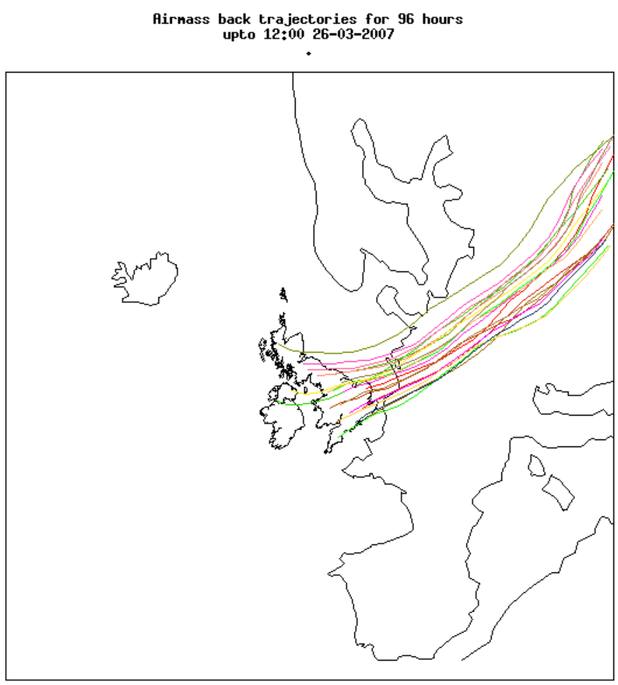


Figure 4c: Air mass back-trajectories for 26th March

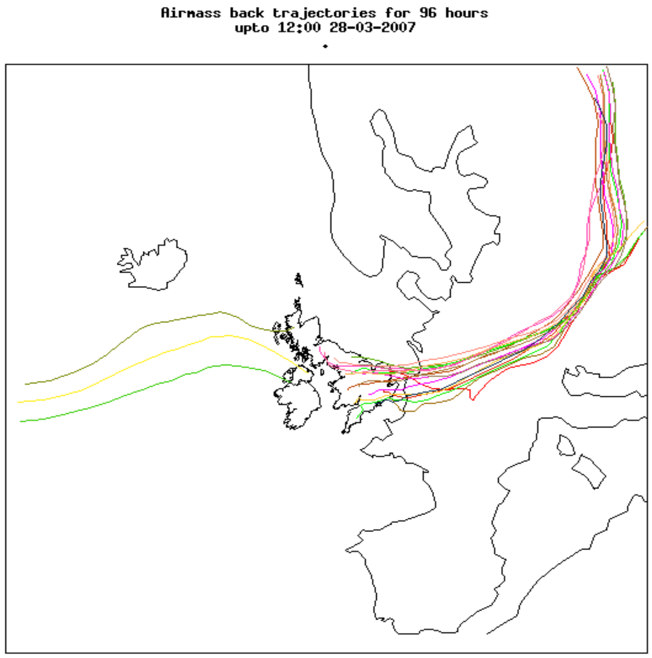


Figure 4d: Air mass back-trajectories for 28th March

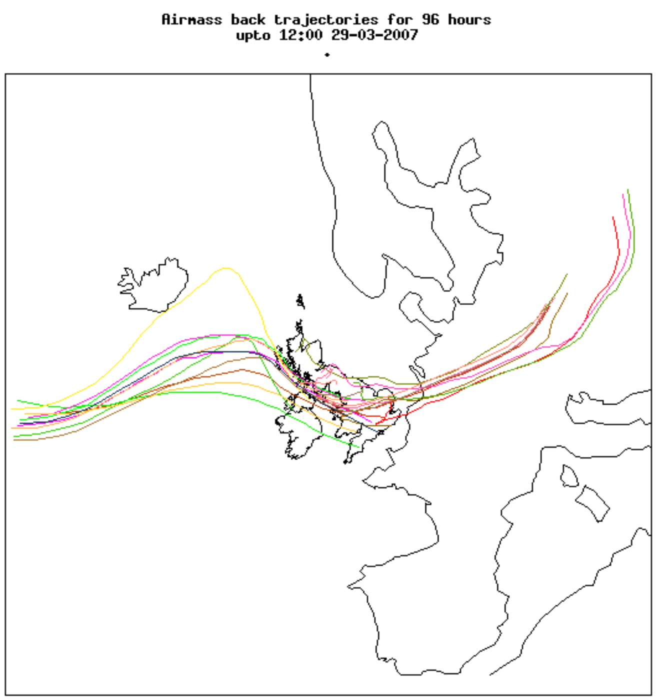


Figure 4e: Air mass back-trajectories for 29th March

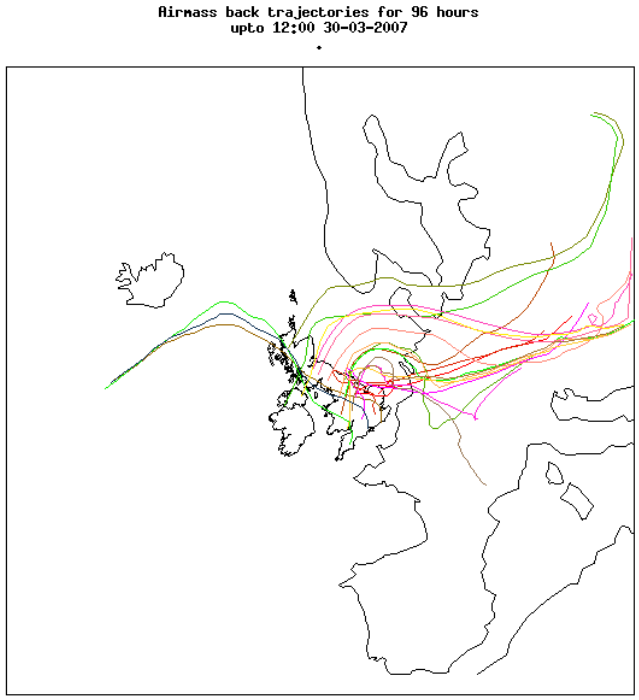


Figure 4f: Air mass back-trajectories for 30th March

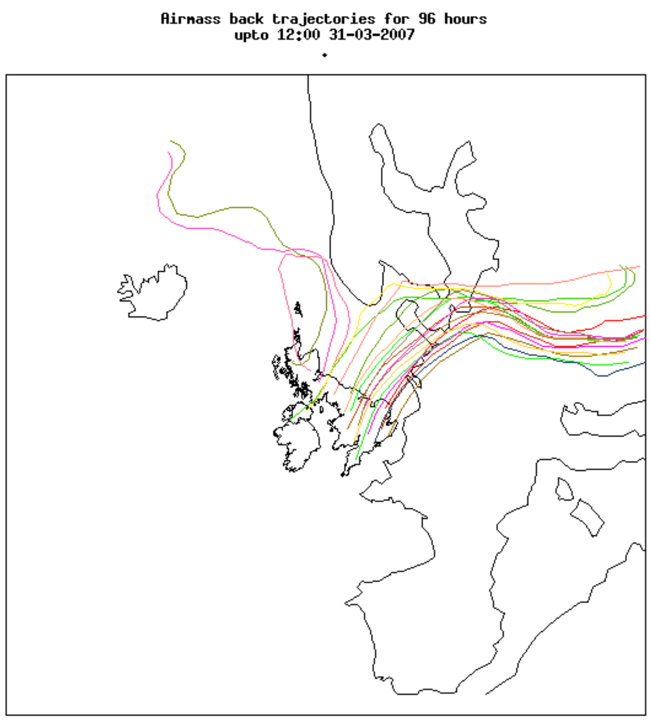


Figure 4g: Air mass back-trajectories for 31st March

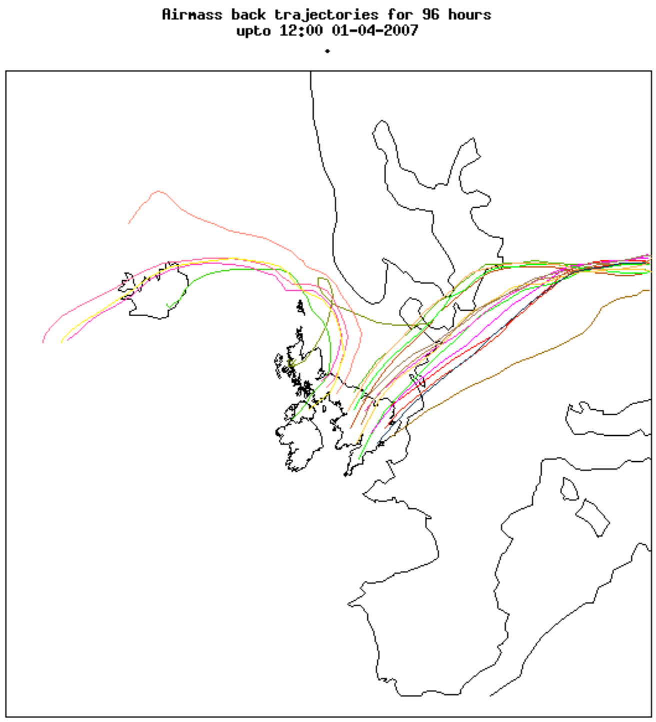


Figure 4h: Air mass back-trajectories for 1st April

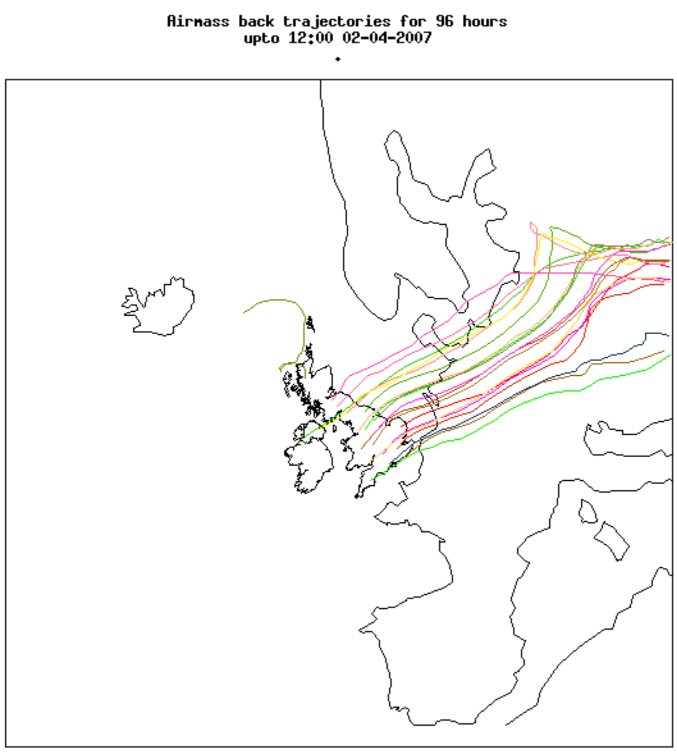


Figure 4i: Air mass back-trajectories for 2nd April

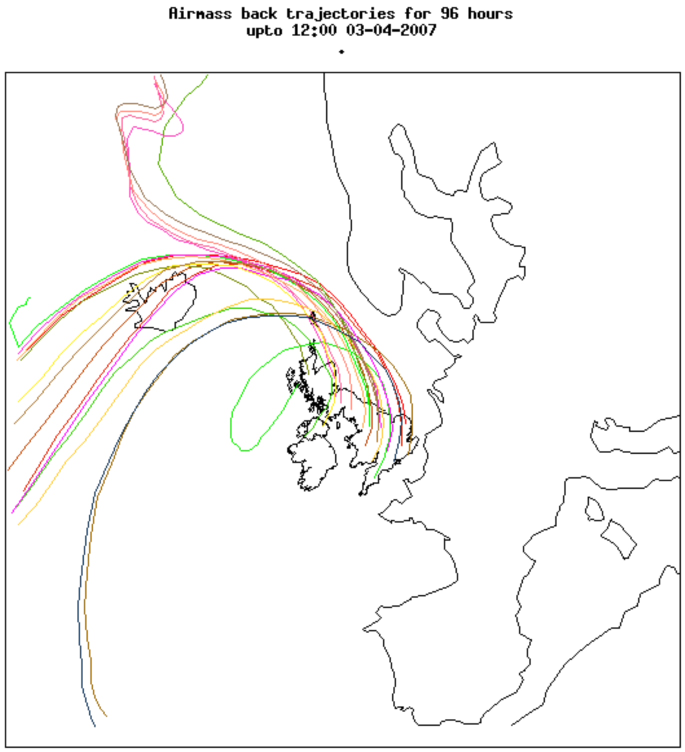


Figure 4j Air mass back-trajectories for 3rd April

At the onset of the pollution episode AEA Energy & Environment and the Met Office considered three hypotheses for the pollution source:

1) Fires in the Ukraine and western Russia
2) Sand storms in northern Africa and northern Saudi Arabia.
3) European pollution combined with 1) and 2) or a combination of all three.

Agricultural fires in the Ukraine and western Russia were observed by Meteosat-8, a second generation geo-stationary satellite, at the end of March (illustrated by the bright spots below in figure 4k). The image was posted on the "Eumetsat" website during the first weekend of the episode. The approximate global position of the fires, based on visual estimations, is shown in figure 4l. On the 20th March MODIS (Moderate Resolution Imaging Spectroradiometer) onboard a polar orbiting NASA satellite identified the beginnings of a sandstorm event in North Africa. The first image of the event, starting around the 20th March, was posted on the "Natural Hazards" website on the 23rd March. An image from a geo-stationary satellite is shown in figure 4m, illustrating the effects of the storm at its height with northerly transport of airborne dust over Turkey and Greece.

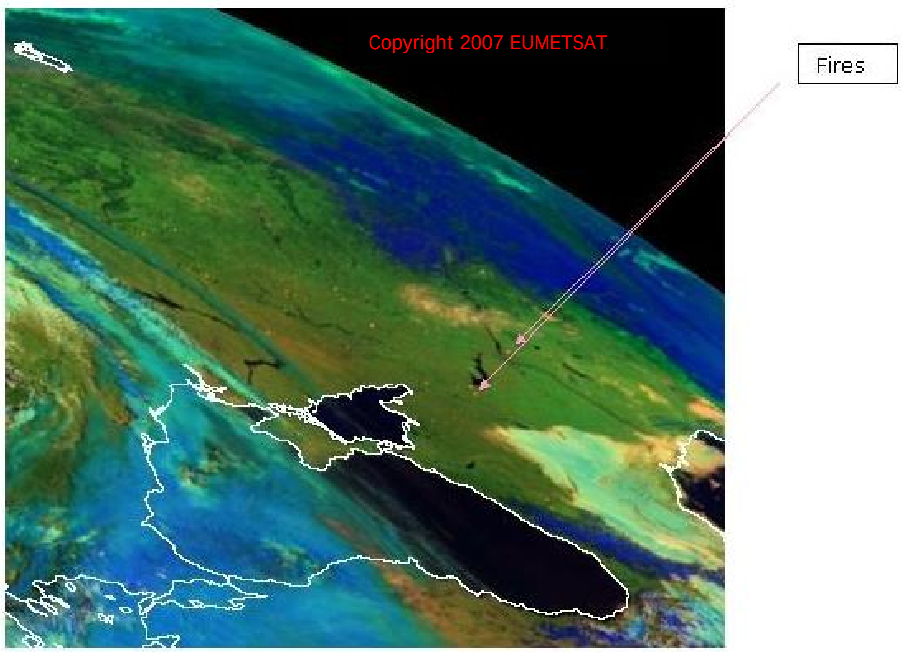


Figure 4k: Fires identified over Ukraine / border with Russia.

Figure 4l: Approximate position of the fires on the Ukraine / Western Russia border (indicated by a cross in a yellow circle).

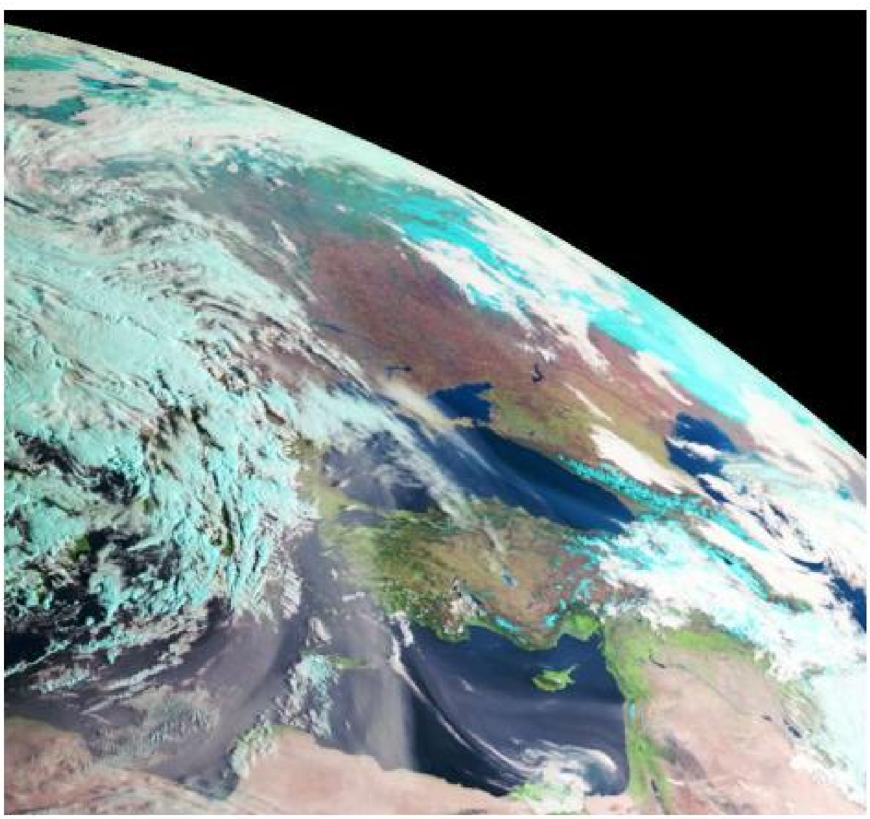


Figure 4m: 21st March 06:00, sand storms over Egypt and Jordan which began on the 20th March.

5. NAME model runs

The atmospheric dispersion model, NAME, was run backwards by the Met Office to determine the history of the air arriving at a selection of UK measurement sites at the time of the initial PM_{10} concentration peaks. Figure 5a shows the history of the air arriving at Narberth between 06UTC and 12UTC on Sunday 25th March 2007, evaluated over the preceding 12 days. This shows that a significant proportion of the air had come from Eastern Europe (Ukraine, Belarus, Poland and the southern edge of Russia). Very small amounts of air had come from the Sahara or the southern region of Europe where the dust storm was reported. This suggests that Saharan dust was not likely to be the primary cause of the high PM_{10} measurements in the UK, although it may have contributed to PM_{10} measurements in the UK on March 25th.

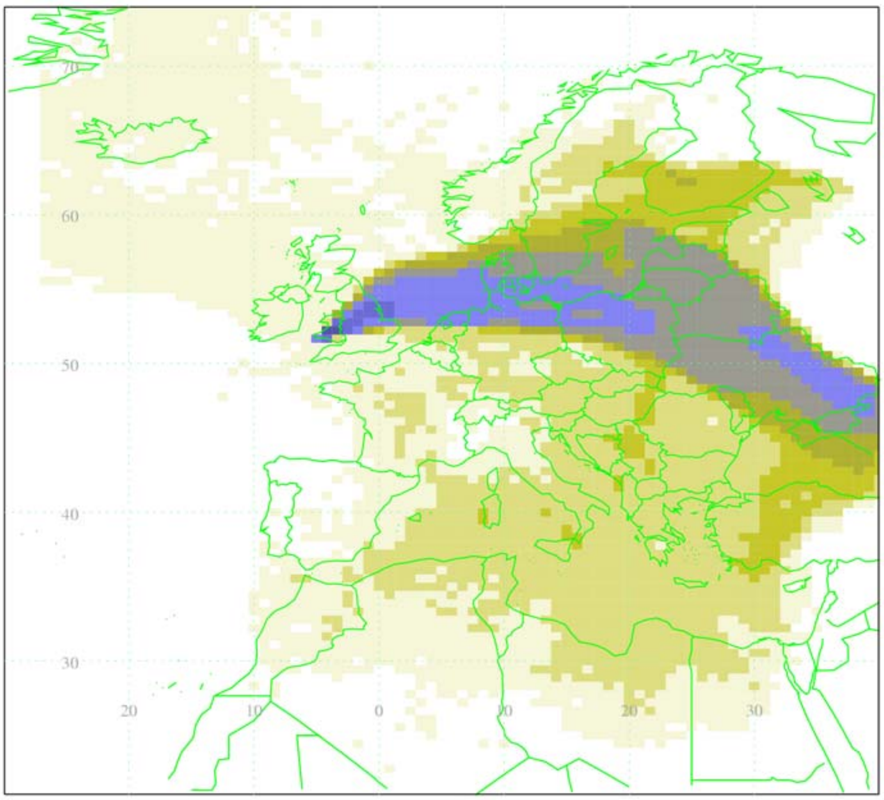


Figure 5a: Air history NAME back analysis for air arriving at Narberth during the measured high PM_{10} concentrations on Sunday 25th March 2007.

The NAME back analysis suggests that fires over the Ukraine and Russia could have contributed to high UK PM_{10} concentrations on Sunday March 25th. It indicates that air from the fire region took between 2 and 5 days to reach the UK giving a source window between March 20th and March 23rd, 2007. To further investigate the possibility of a Russian / Ukrainian source, NAME was run forwards with a pollution source covering the fire region (30° E to 43° E, 46° N to 54° N) during this time window. A release over a height of 0 to 2000 m was chosen to model the rise of the buoyant smoke plumes from the fires. Comparisons of observed and NAME predicted time series at Narberth, Birmingham and London Bexley are shown in Figures 5b, 5c and 5d. NAME predicted a peak in time series concentrations at the three locations. The timing of the peak at Narberth agreed very well with the observed peak. The NAME predicted peak at Birmingham and London Bexley occurred roughly 5 and 9 hours earlier, respectively, than the observed peak in PM_{10} concentrations. In addition, Birmingham, and to some extent, Narberth showed further predicted peaks during Monday 26th March.

The NAME modelling does not take into account any variation in intensity of the fires or any estimation of the amount of material released. The estimated source area may also have been subject to some errors. However, the back analysis and the time series signatures both suggest that fires in the Ukraine and Russia made a significant contribution to UK PM_{10} concentrations during the period of the measured pollution episode.

Narberth

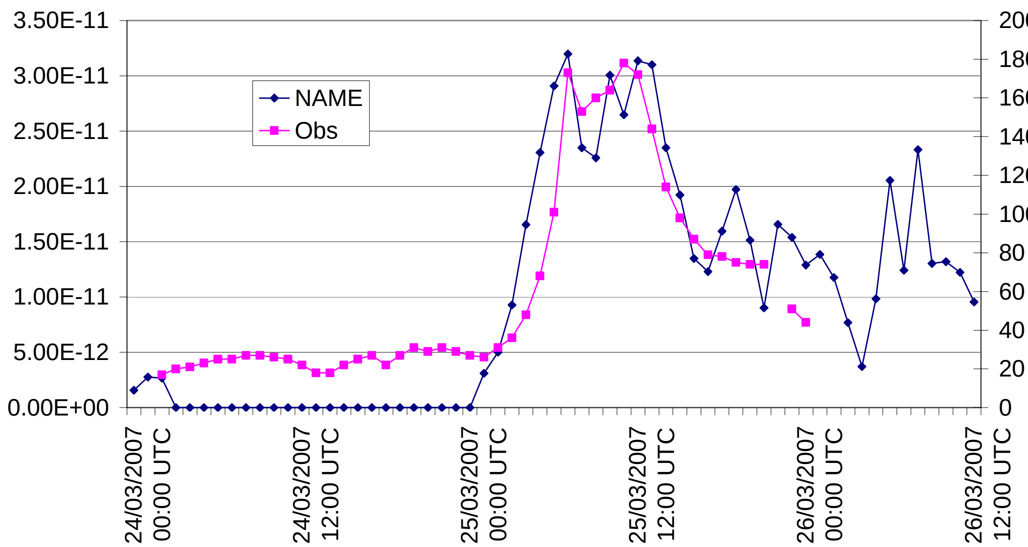


Figure 5b: Comparison of NAME and observed time series at Narberth during the period 24th - 25th March 2007.

Birmingham

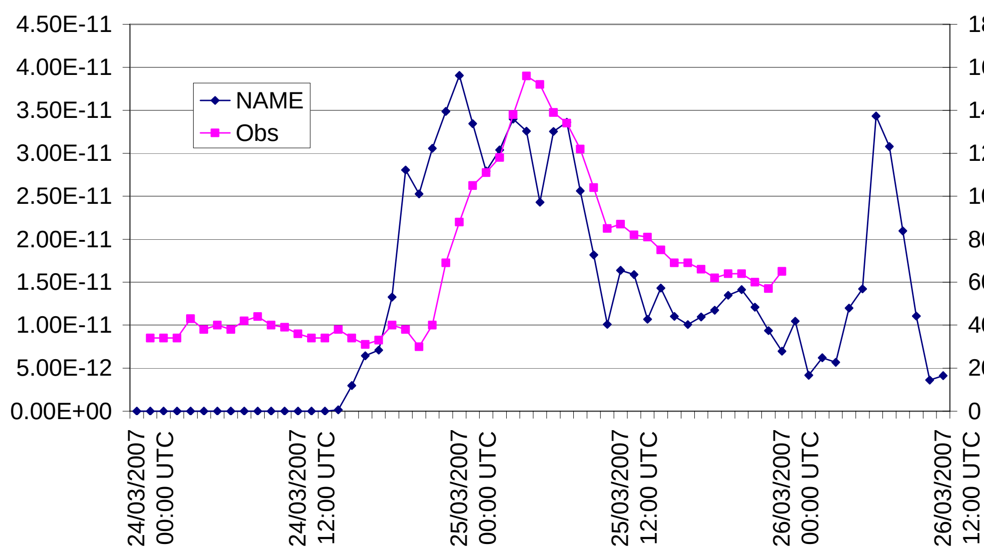


Figure 5c: Comparison of NAME predicted and observed time series at Birmingham during the period 24th - 25th March 2007.

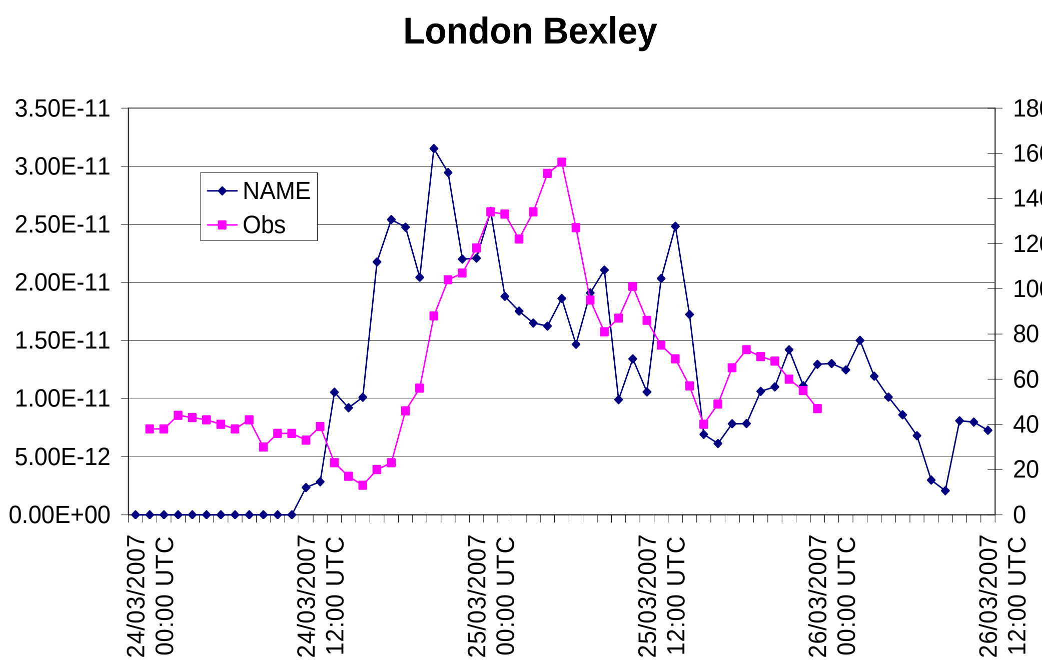


Figure 5d: Comparison of NAME predicted and observed time series at London Bexley during the period 24th - 25th March 2007.

Further modelling studies were performed by the Met Office using the dust scheme within NAME to investigate the effects on the UK of the Saharan dust storm in mid/late March. A run was performed initialised at 0 UTC on the 19th March. Figure 5e shows the uplift and transport of dust to the UK. The initial manifestation occurred on the 19th March with the plume being advected across the Mediterranean and towards Russia and the Ukraine. This suggested that the dust from the Sahara may well have mixed with biomass burning aerosol in these regions en route to the UK. Although the relative contribution of air from the Sahara to the UK is likely to have been small, a fraction of the PM observed in the UK around March 25th may have had this origin.

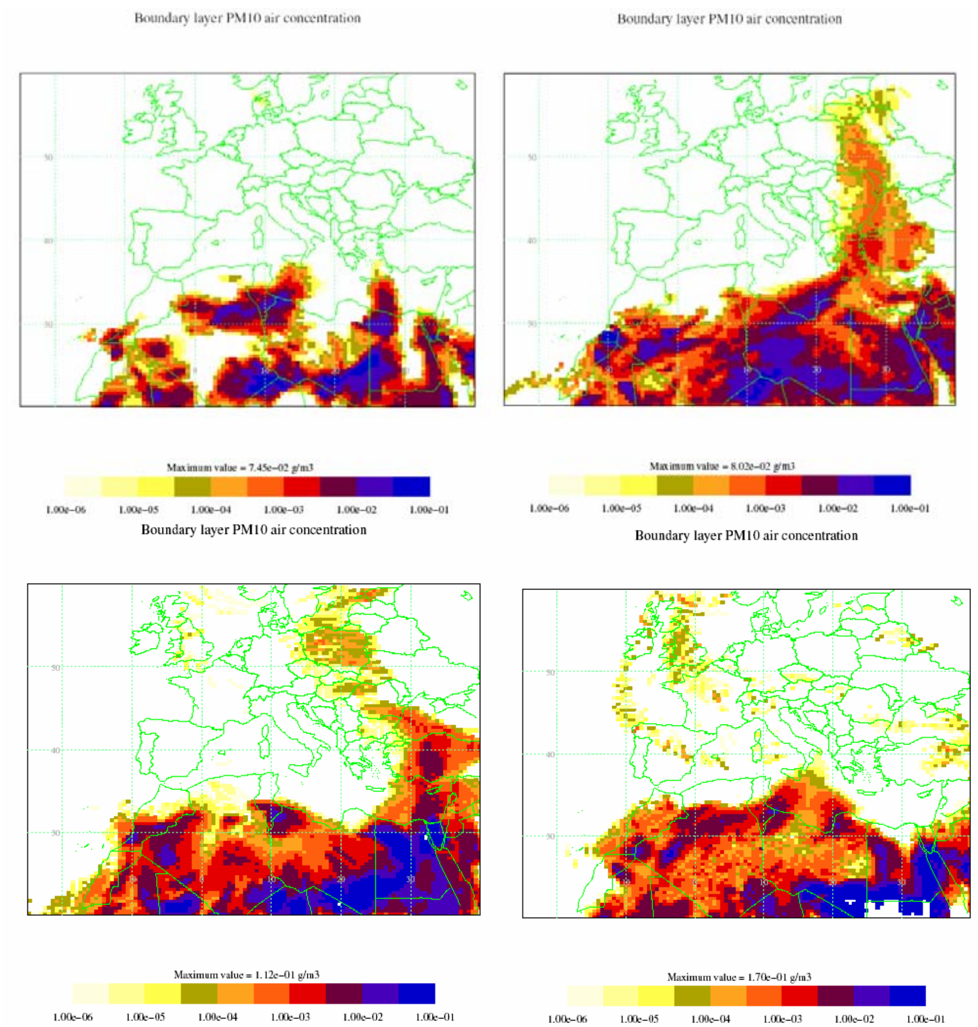


Figure 5e**:** Output from the NAME model at 0 UTC 20.3.07, 12 UTC 21.3.07, 18 UTC 23.3.07 and 0 UTC 25.3.07

The dust scheme determines the amount of dust to be lifted into the atmosphere based on the land surface properties together with surface wind speeds. Particle size distribution, sedimentation and deposition (dry and wet) are also represented but as with the uplift parameterisation, there are uncertainties associated with each of these factors. However, despite these uncertainties, in this instance, the dust model seemed to represent the initial dust effluence reasonably well (see Figure 5f).

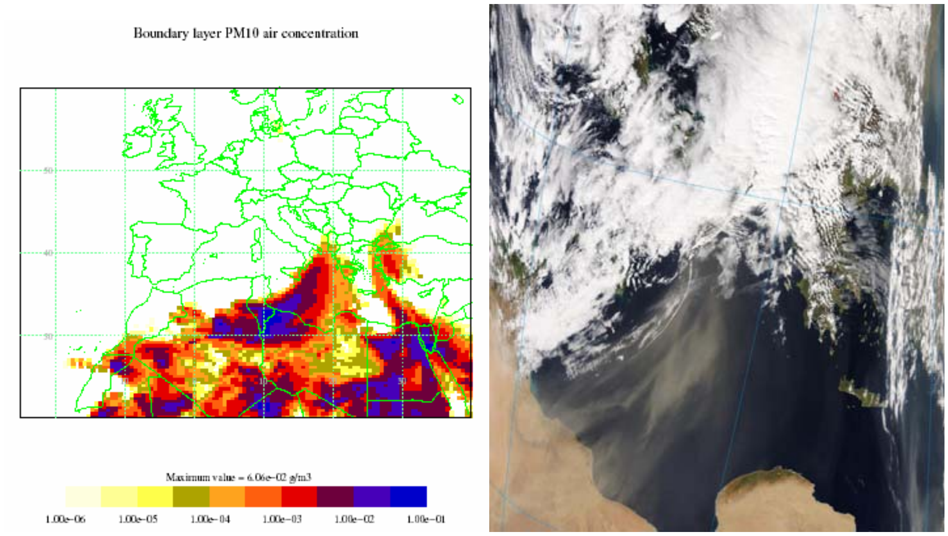


Figure 5f: Output from the NAME model at 12 UTC 20.3.07 compared with MODIS image for the coast of Libya (c/o NASA) for the same time.

After several days of continued elevated PM_{10} concentrations following the initial onset of the episode, the Met Office once again ran the NAME model to study high PM_{10} levels on Wednesday March 28th at locations in Northern Ireland, Scotland and northern England. The model was run backwards from Belfast, Glasgow, Middlesbrough and Stoke-on-Trent to determine the history of the air arriving at these locations at the time of the PM_{10} concentration peaks.

Figure 5g shows the air history map for air arriving at Stoke-on-Trent at the time of the PM_{10} concentration peak on March 28th. Most of the air had come from an easterly direction over much of Europe (Russia, northern Ukraine, Belarus, Poland, Slovakia, the Czech Republic, Germany and the Netherlands). It is likely, therefore, that general pollution from the continent also played a part in the UK pollution episode levels.

The main air source over Russia and the Ukraine was slightly further north than in the previous study for air arriving at UK sites on 25th March. The air history map suggests that fires in Russia and the Ukraine may have continued to contribute to PM_{10} concentrations on March 28th. Very little air had come from the Sahara or the southern regions of Europe where a dust storm had been reported some days earlier. Hence it seems less likely that Saharan dust contributed significantly to the high PM_{10} concentrations over the UK during the second part of the episode.

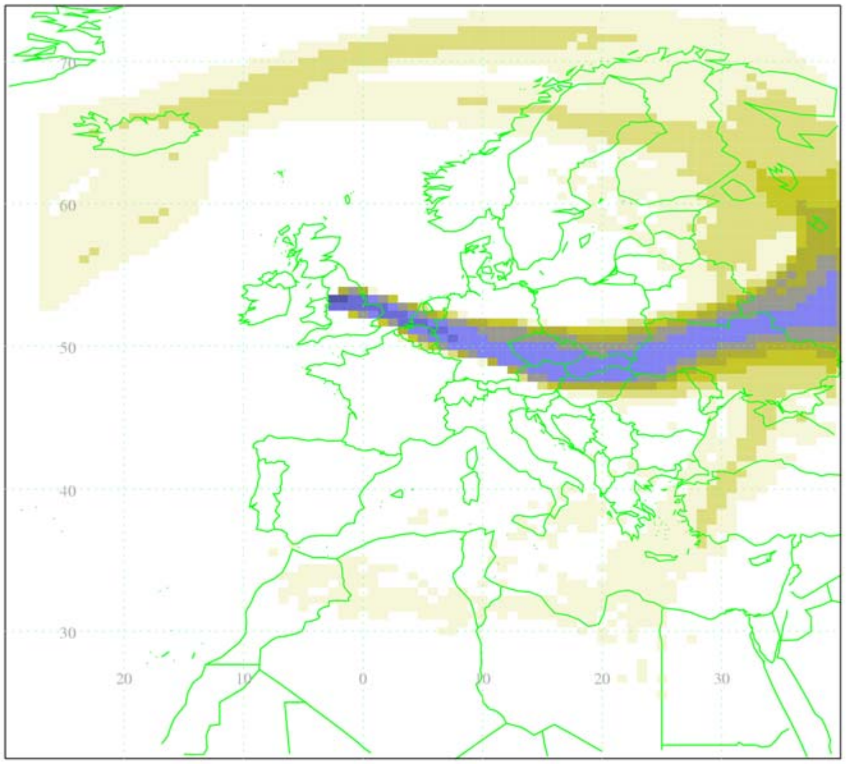


Figure 5g: Air history NAME back analysis for air arriving at Stoke-on-Trent during the measured high PM_{10} concentrations on Wednesday 28th March 2007.

NAME was then run forwards again with a pollution source over the approximate fire region in Russia and the Ukraine. It was noted that if the fires had extended further north than the estimated modelled release site, then they would have made a more significant contribution to PM_{10} concentrations at Glasgow, Middlesbrough and Stoke on Wednesday 28th March. A release over a height of 0 to 2000 m was again chosen to model the rise of the buoyant smoke plumes from the fires. Comparisons of observed and NAME predicted time series at Belfast, Glasgow, Middlesbrough and Stoke-on-Trent are shown in Figures 5h to 5k. In general NAME predicted a period of elevated pollution between Sunday March 25th and Wednesday March 28th inclusive, which was in agreement with moderate to high levels of PM_{10} observed at many UK sites throughout this period. This suggested that the Ukraine and Russian fires contributed, in general, to PM_{10} concentrations over Northern Ireland, Scotland and northern England, over the period. The peaks in PM_{10} concentration within this period were not always well captured. In particular, the peaks on Wednesday March 28th at Stoke-on-Trent and Middlesbrough were not well captured. This was thought to be due to an error in the fire source term as discussed above. NAME also predicted peaks in PM_{10} concentrations which were not observed (see for example the NAME predicted peak at Stoke-on-Trent on Tuesday 27th March shown in Figure 5k). In the generic NAME model used no account is taken of any variation due to source strength nor any deposition of material which may be significant, particularly if the plume was washed out by precipitation.

Also shown in figures 5l and 5m are a comparison of NAME predictions and observed PM_{10} concentrations at the previously studied locations of Narberth and Birmingham. It was noted that, as for Stoke-on-Trent, NAME also predicted a large peak at Birmingham on Tuesday March 27th which was not observed in the measurements. The agreement between NAME and the observations regarding the timing of the sudden rise in concentrations on the morning of March 25th, the timing of the sudden drop in concentrations overnight on Wednesday 28th / Thursday 29th March and the generally elevated concentrations in between was good evidence that fires in the Ukraine and Russia contributed to the elevated UK PM_{10} concentrations.

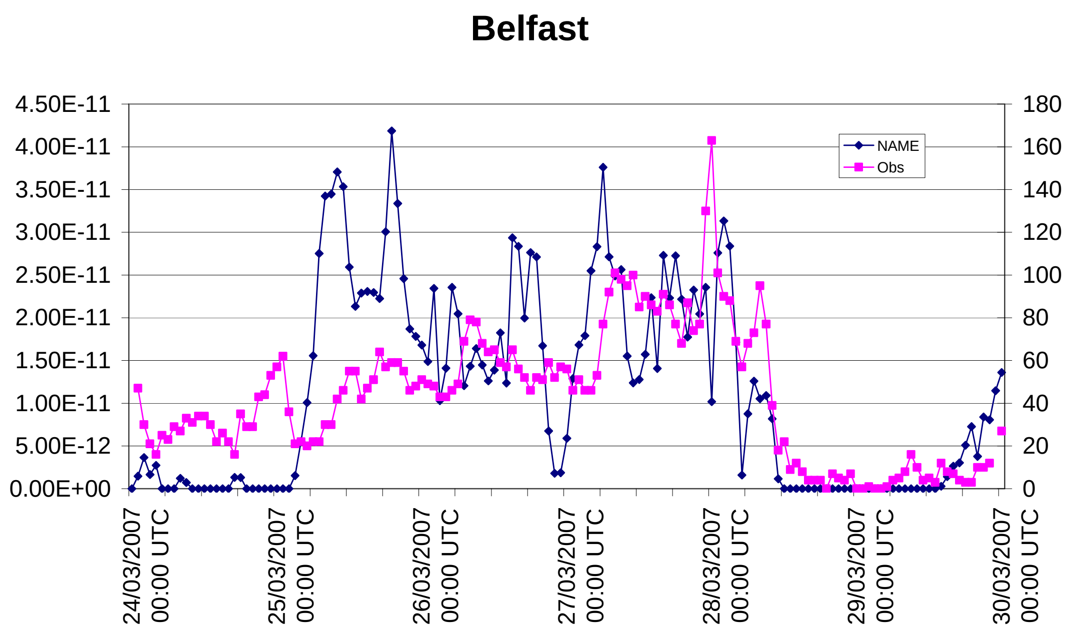


Figure 5h: Comparison of NAME predicted and observed time series at Belfast during the period 24th - 29th March 2007.

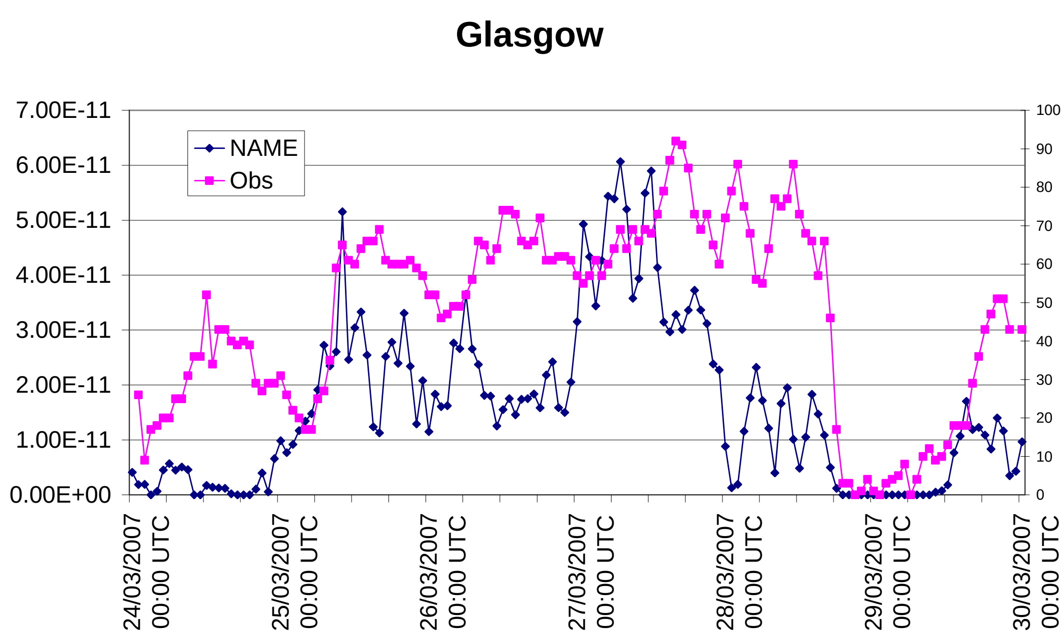


Figure 5i: Comparison of NAME predicted and observed time series at Glasgow during the period 24th - 29th March 2007.

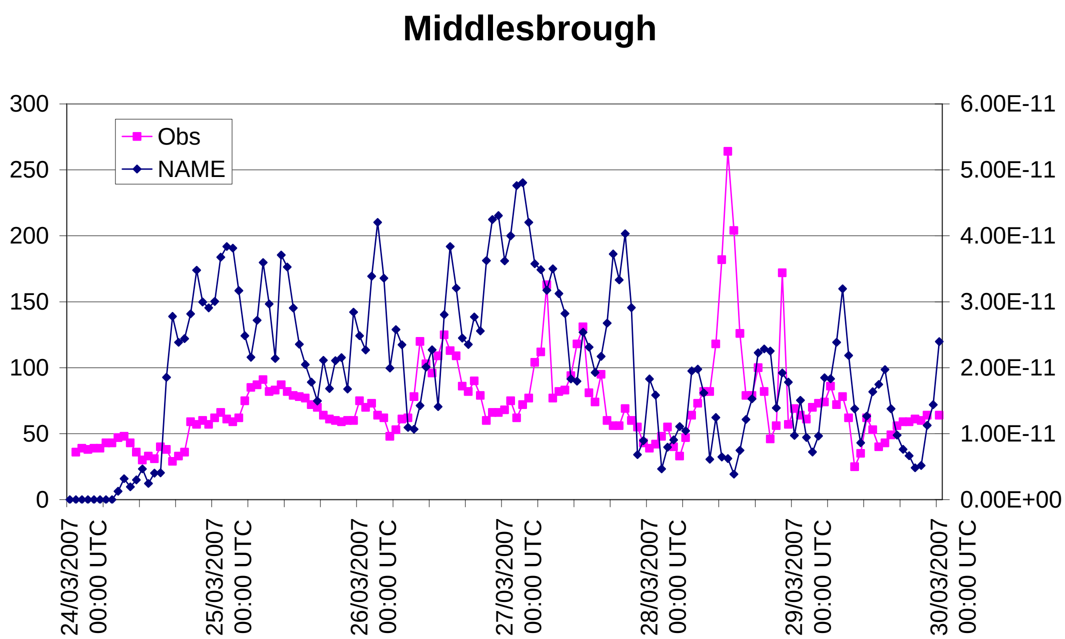


Figure 5j: Comparison of NAME predicted and observed time series at Middlesbrough during the period 24th - 29th March 2007.

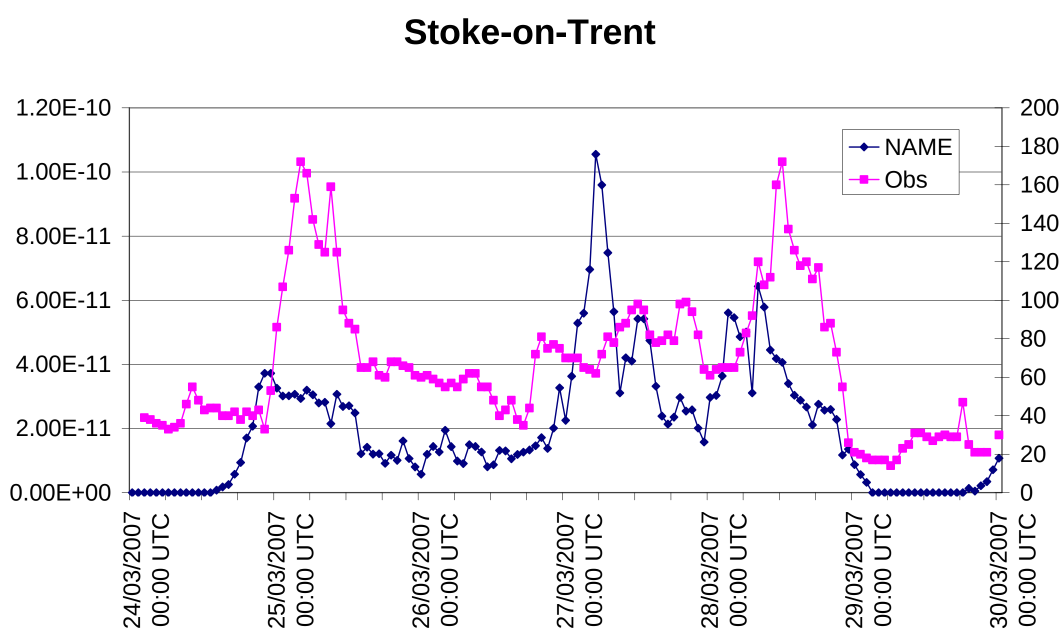


Figure 5k: Comparison of NAME predicted and observed time series at Stoke-on-Trent during the period 24th - 29th March 2007.

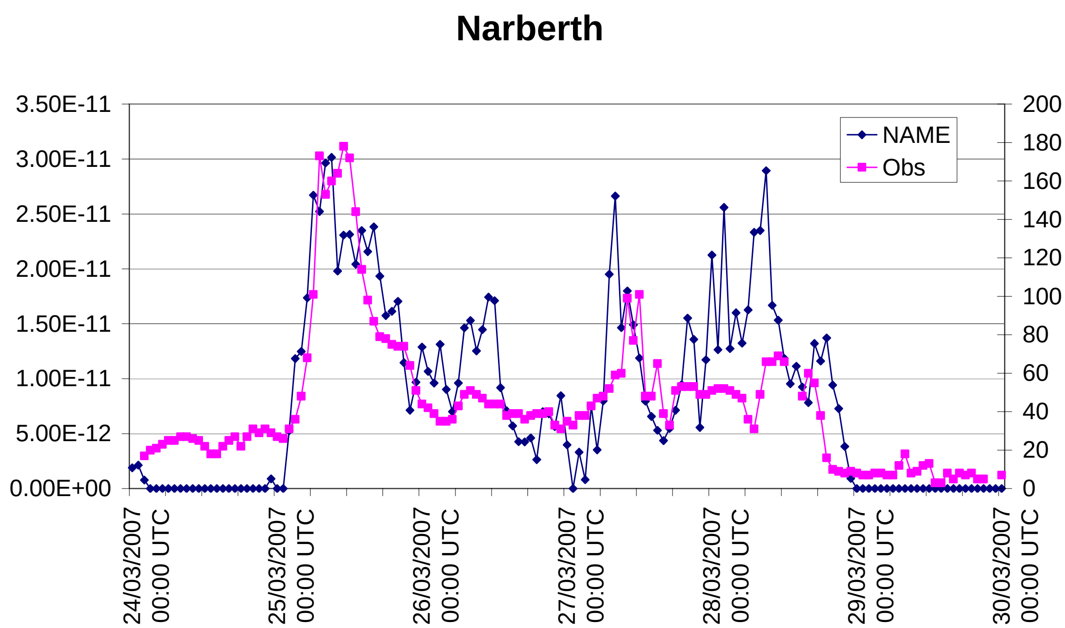


Figure 5l: Comparison of NAME predicted and observed time series at Narberth during the period 24th - 29th March 2007.

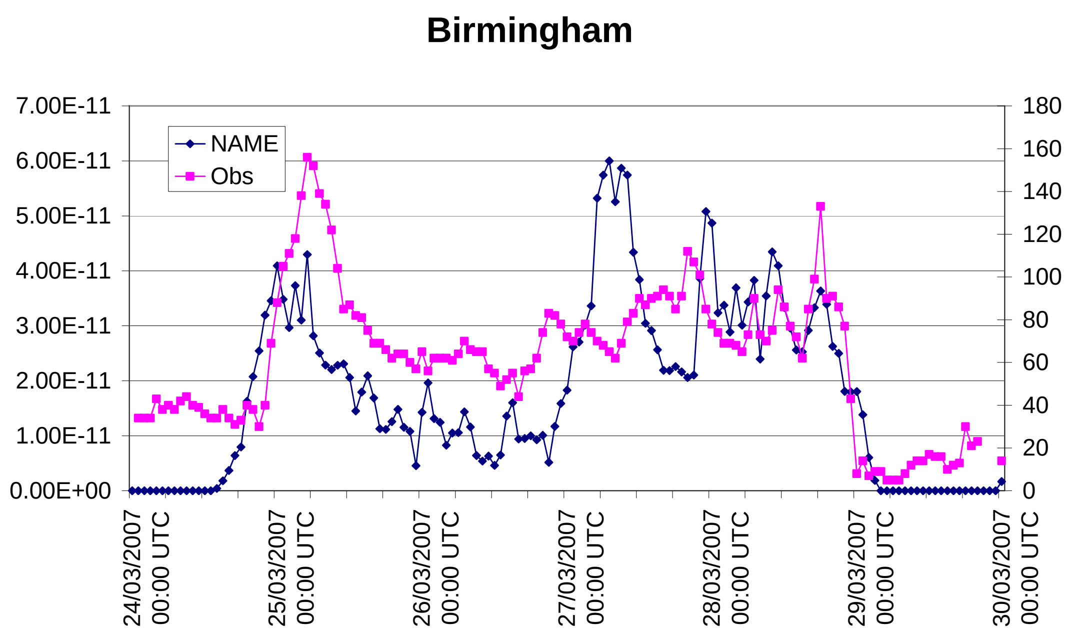


Figure 5m: Comparison of NAME predicted and observed time series at Birmingham during the period 24th - 29th March 2007.

6. Tracking the episode from satellite images

Please note that many of the high resolution colour images which follow have been sourced from the MODIS instrument onboard the NASA “Terra” and “Aqua” satellites, the SeaWiFS instrument onboard the SeaStar spacecraft and images obtained from the “MSG service” which disseminate broadcasts from a Meteosat Second Generation geo-stationary satellite. A summary of the key features of these satellites is shown below:

- MODIS (or Moderate Resolution Imaging Spectroradiometer) is a key instrument aboard the Terra and Aqua satellites. Terra's orbit around the Earth is timed so that it passes from north to south across the equator in the morning, while Aqua passes south to north over the equator in the afternoon. Terra MODIS and Aqua MODIS view the entire Earth's surface every 1 to 2 days, acquiring data in 36 spectral bands, or groups of wavelengths.

- The SeaStar spacecraft, developed by OSC, carries the SeaWiFS instrument and was launched to low Earth orbit on board an extended Pegasus launch vehicle on August 1, 1997.

- Geo-stationary satellites are positioned high (36,000 km) above the equator so they can see the whole of one side of the earth. Since they orbit the earth at the same speed as the earth rotates they appear to be stationary above the same point. Five satellites are used to give complete global coverage. However the resolution is best at the equator; further north the resolution degrades until it is impossible to see the north or south pole.

The images obtained from the SeaWifs “Ocean Colour” website were downloaded from the two required east/west earth’s globe sections then spliced together using photo-editing software. The image was then cropped to highlight the area of interest. Missing (black) sections in the final images are outside of the satellite field of view. These composite images provide the best “true” colour pictures from the Atlantic to western Russia.

Geo-stationary satellite images are artificially coloured but still give a good visual indication of global particulate events. The images shown in this report have been cropped from the whole earth globe. These images are freely available on the Dundee Satellite Receiving Station website (www.sat.dundee.ac.uk).

MODIS satellite images are the highest resolution pictures freely available on the internet. The pictures in this report have again been obtained via the Dundee Satellite Receiving Station website.

The following section looks at the available satellite images and synoptic weather charts to track the progress of the episode.

Figure 6a shows the synoptic situation at 12Z on March 20th with low pressure over most of Europe. Figures 6b1 and 6b2 show a sandstorm in northern Africa clearly seen travelling northwards into the spiral arm of the depression on the following day. These days appear to mark the start of the build up of the particulates from the east that reached the UK on the 24th and 25th March.

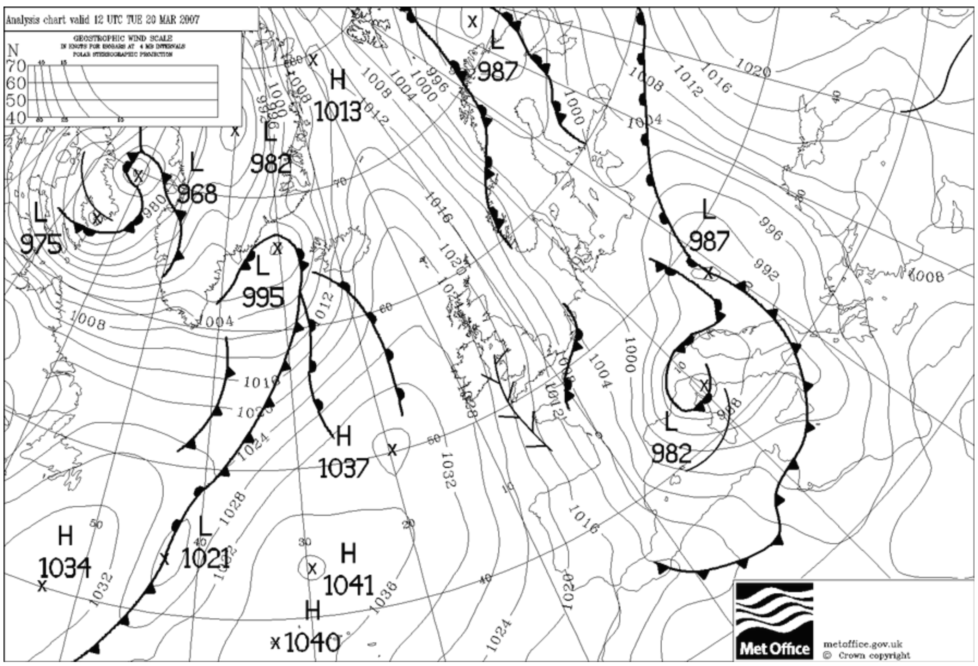


Figure 6a: 20th March

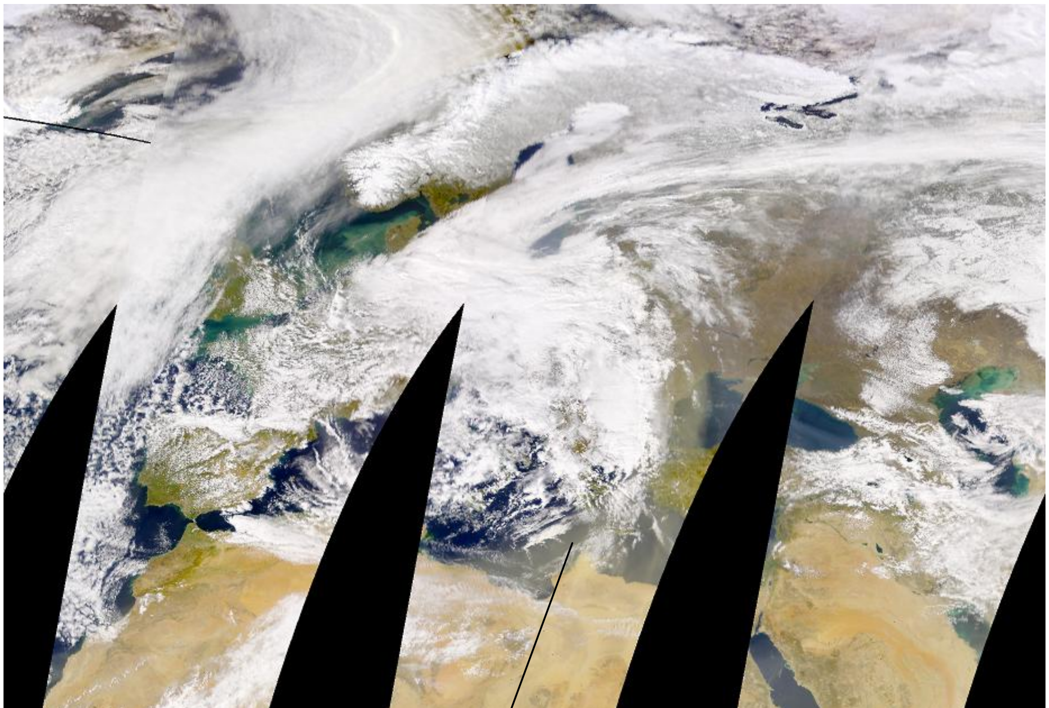


Figure 6b1: 21st March

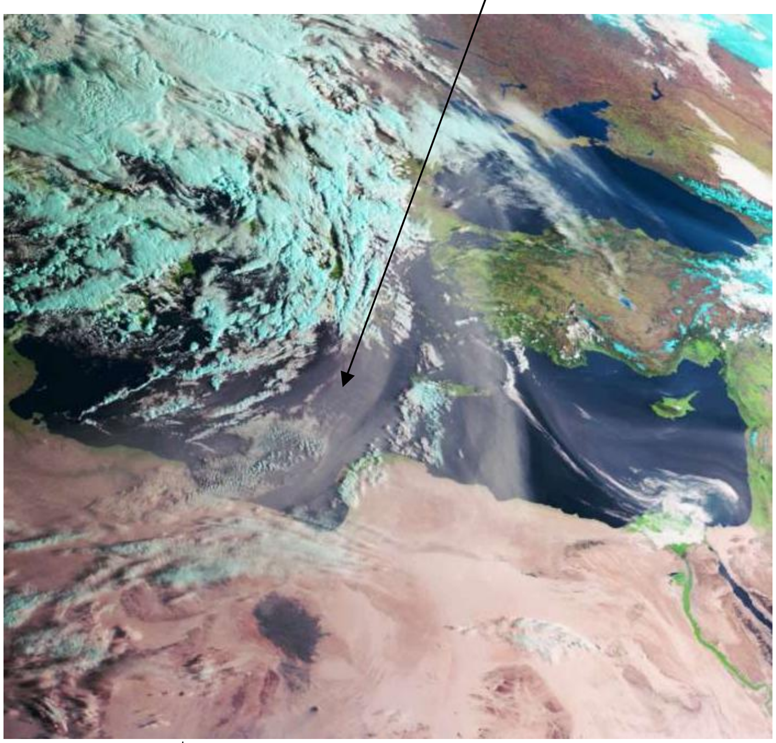


Figure 6b2: 21st March

Figure 6c shows the air pressure situation on the 24th March at midday, with low pressure over continental Europe and high pressure over Scandinavia.

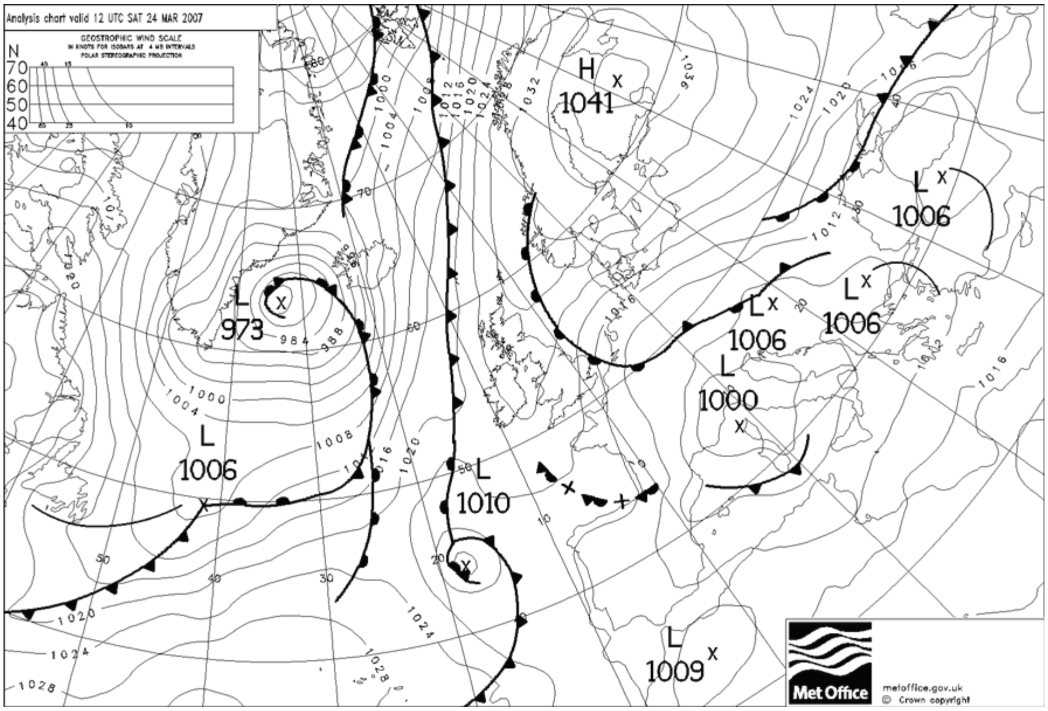


Figure 6c: 24th March

Saturday 24th March was the first day that the episode was recorded in the UK. Norwich Centre, in East Anglia, measured its first elevated hourly average in the afternoon, at around 2 p.m.. Harwell, in the south east of England measured the onset of the particulate laden air at 9 p.m. on the Saturday evening. The initial wave reached sites in the north of England by 11 p.m. on the same evening. Sites in the north west of England generally measured higher PM_{10} levels than sites in the north east during this period.

Figures 6d1 and 6d2 show the satellite imagery at midday on the 24th, about the time the pollution was measured in East Anglia. Both images show what appears to be a significant concentration of haze built up behind the warm front that was advancing towards the UK from the east. More haze can be seen over eastern mainland Europe at this stage in both images.

Figure 6e shows the position of the advancing warm front at 6 p.m.. The front had, by then, covered the whole of the east side of England. Sites in the south east of England had measured the onset of the episode two hours earlier. By midnight, as shown in figure 6f, the warm front had reached all of England except the south west. By 6 a.m. on Sunday morning the advancing warm front, behind which the particulate laden air was trapped, had begun to break up over Scotland and before reaching the shores of Northern Ireland. This may explain the reason for the generally lower levels of particulates measured in Scotland during the onset and the relatively low initial peak measured at Lough Navar, in Northern Ireland on the afternoon of Sunday the 25th. With the break up of the warm front over Scotland the intensity of the particles measured at ground level to the west of the area of the break up would have been expected to be less.

Satellite images shown in figures 6g1 and 6g2 show the break up of the front towards the north of the UK at 12 p.m. on the 25th. Figure 6g3 shows in more detail what appears to be a further cloud of dust/haze advancing over eastern Europe towards the UK on the 25th.

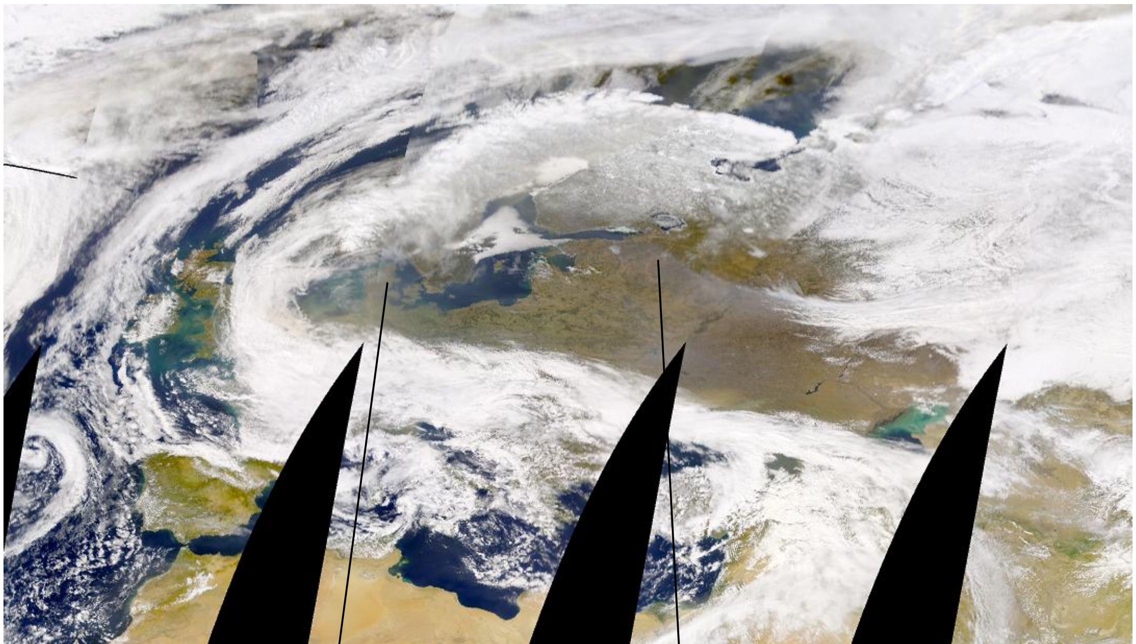


Figure 6d1: 24th March

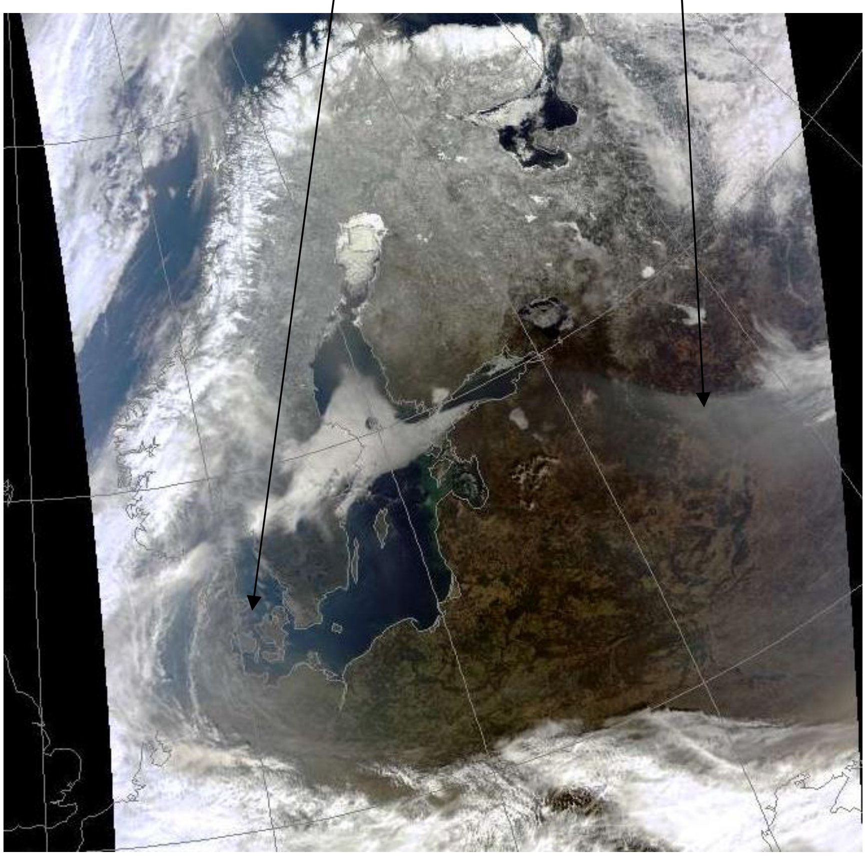


Figure 6d2: 24th March

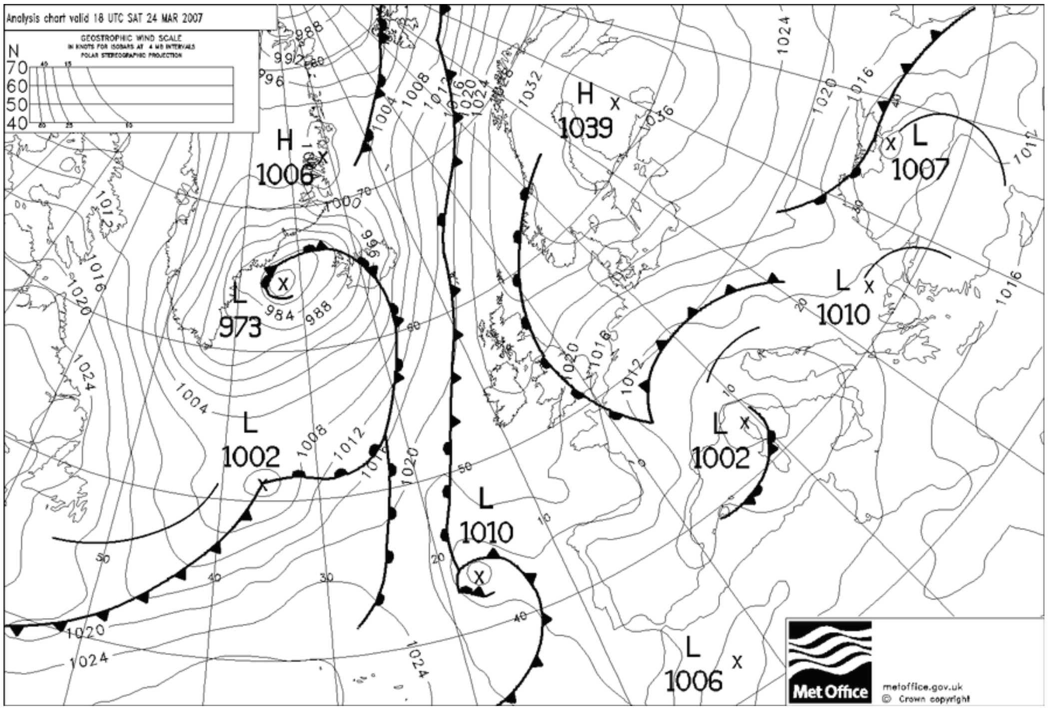


Figure 6e: 18:00 on the 24th March

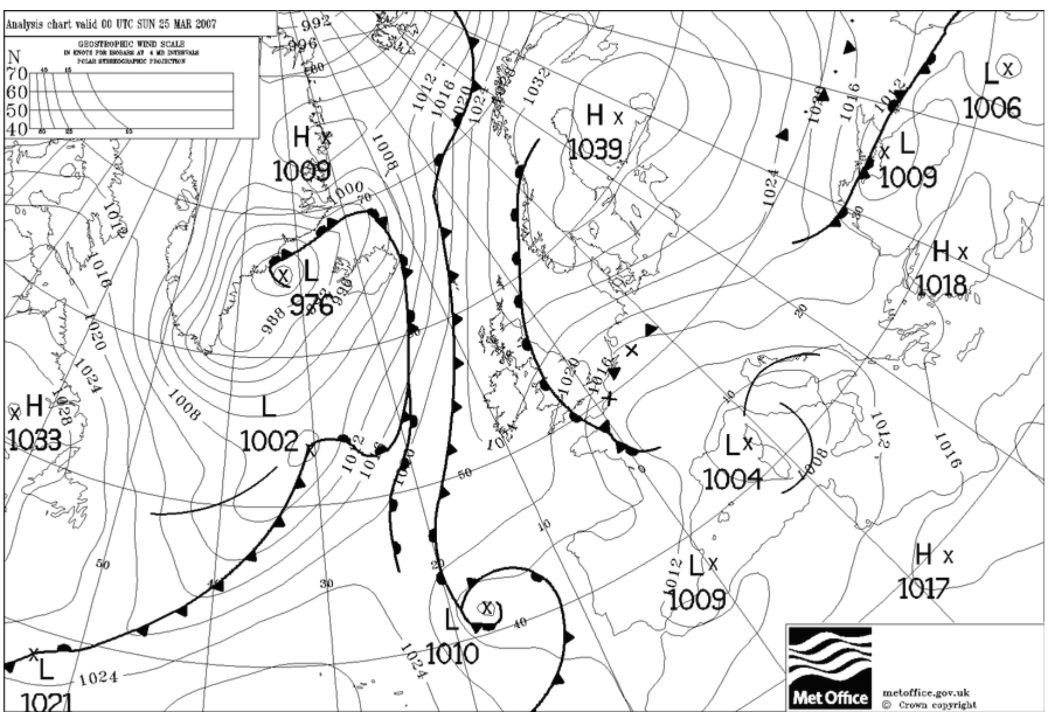


Figure 6f: 00:00 on the 25th March

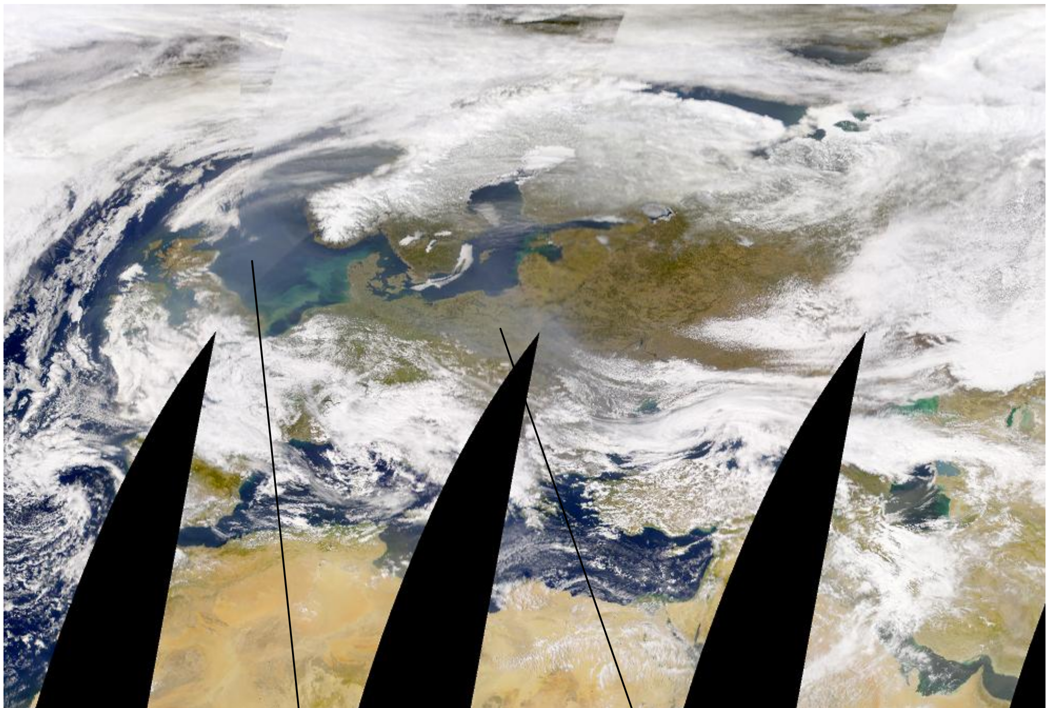


Figure 6g1: 25th March

Figure 6g2: 25th March

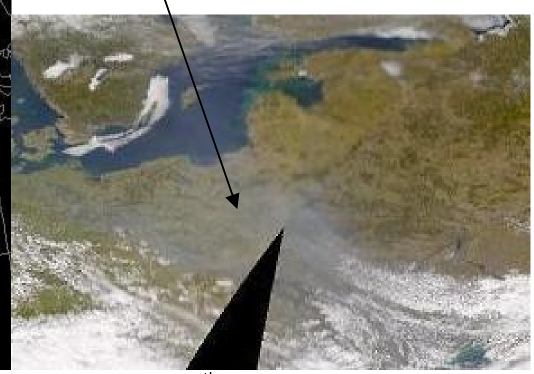


Figure 6g3: 25th March

By midday on the 26th the warm front had dissipated and a cold front was present to the west of the UK, as shown in Figure 6i. Satellite images suggest that much of the particulate laden air was over the North Sea and the UK itself (see figures 6h1 and 6h2), with more haze passing over Eastern Europe from a non-European source further to the east, as shown in Figure 6h3.

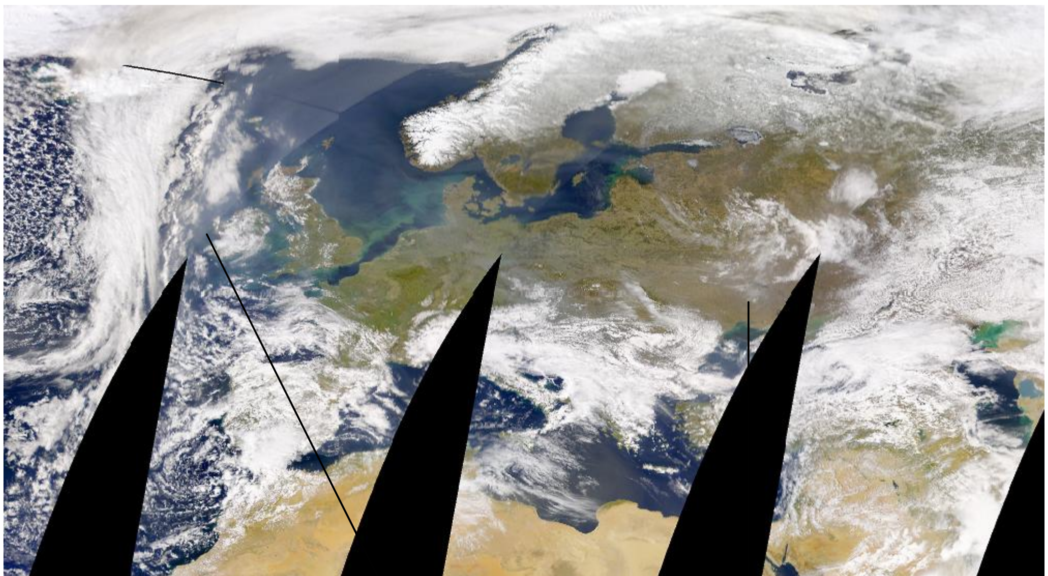


Figure 6h1: 26th March

Figure 6h2: 26th March

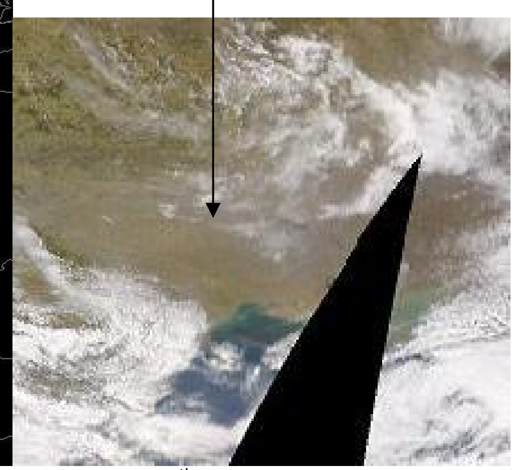


Figure 6h3: 26th March

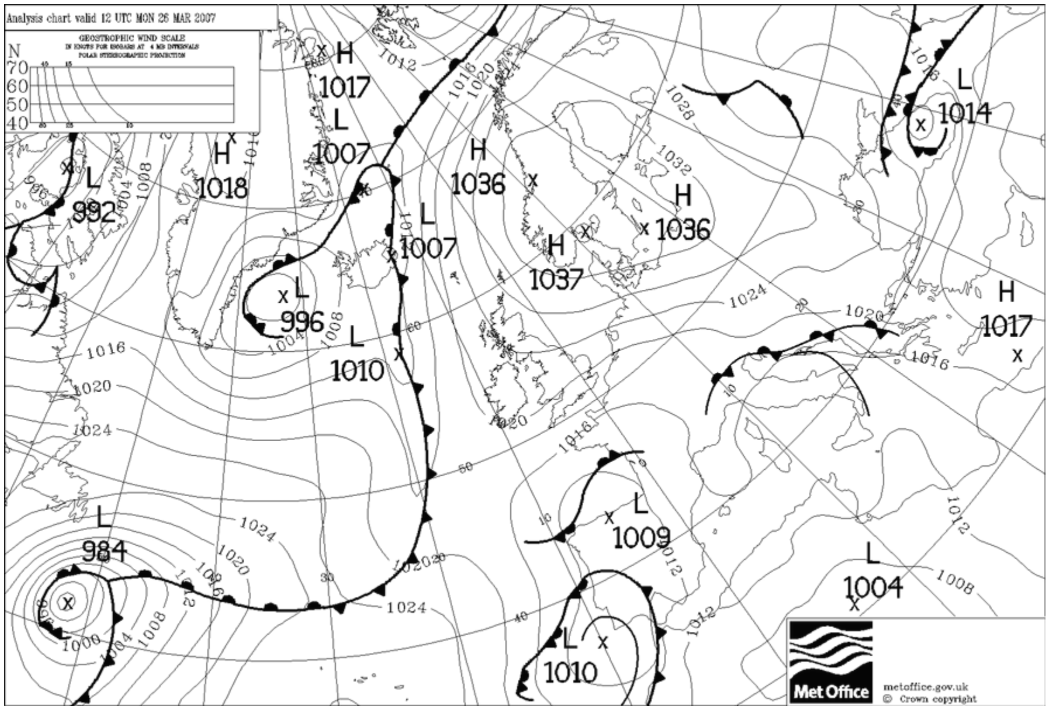


Figure 6i: 12:00 on the 26th.

Measurements show that over the following days the position of the advancing cold front was crucial to the concentrations measured across the UK. Behind the cold front, which was advancing from the west, the air was clear and therefore particulates were trapped on the eastern side of this boundary. Figures 6j1 and 6j2 show the general haze seen over the UK on the 27th after it had passed over continental Europe. Figure 6j1 also shows sand spiralling north eastwards towards Europe from a sandstorm in North Africa. Figure 6k2, taken at midday on the 28th, shows clear air to the west of the UK and a low pressure centre just north of Spain drawing the particulate laden air across the UK and out to the south-west. All the figures of 6k show a heavy concentration of white haze, thought likely to be smoke, over Eastern Russia and the Ukraine and more over northern mainland Europe.

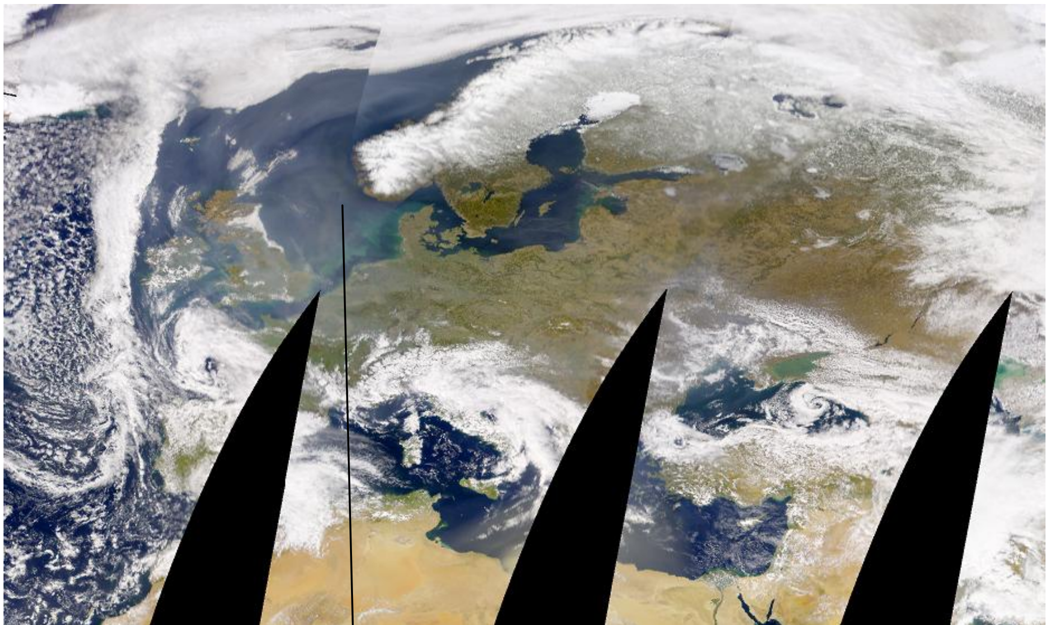


Figure 6j1: 27th March

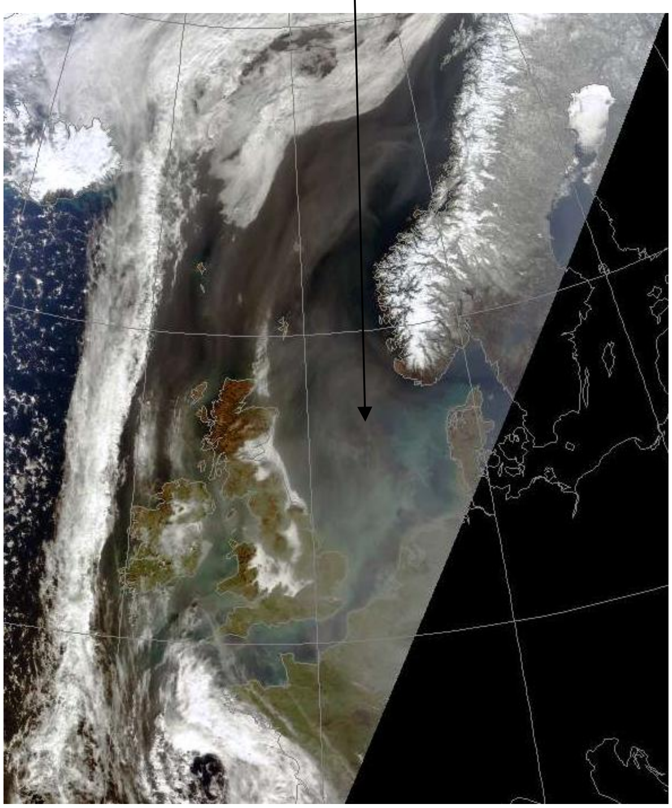


Figure 6j2: 27th March

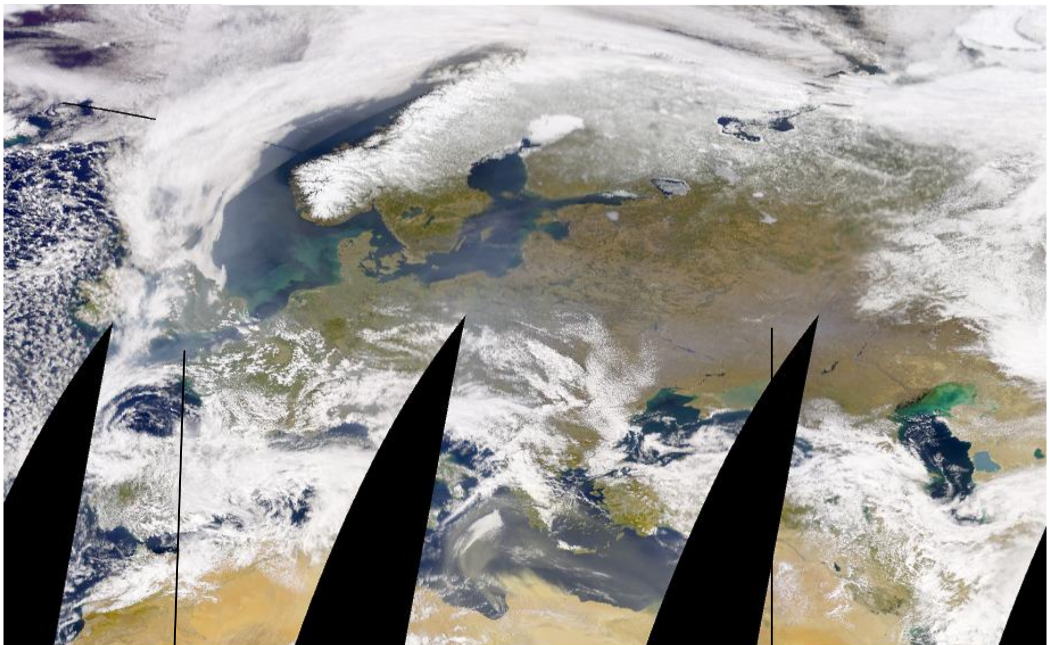


Figure 6k1: 28th March

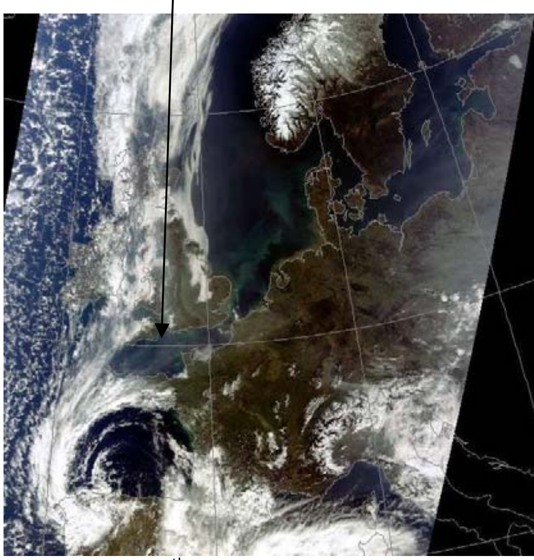


Figure 6k2: 28th March

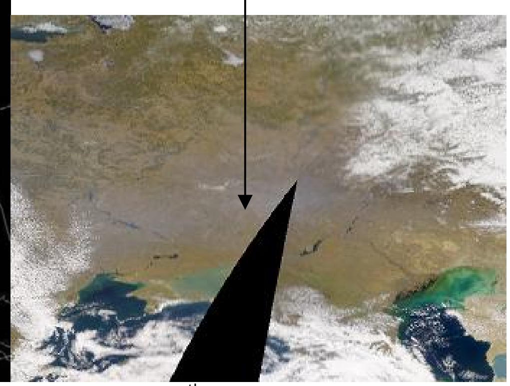


Figure 6k3: 28th March

Satellite images taken on the Thursday 29th, shown in figures 6l1 and 6l2 were the clearest indication of the source of the pollution during the whole period of the episode. A trail of smoke initially appears to originate near the border of Russia and Kazakhstan, as marked with a red cross on figure 6l1. On closer inspection of the pressure chart seen in figure 6m however, it seems more likely that some of the smoke from the vicinity of the Ukraine, where the highest concentration of smoke is seen in the images, was trapped behind an occluded front that was travelling southwards. The pressure chart in figure 6m shows the position of the cold front across the UK at midday, with only Scotland and the north east of England exposed to the particulate laden air.

On Friday 30th March, as seen in figure 6n1, much of the smoke from the Ukraine area had drifted northwards and was being gradually drawn westwards over Sweden and Denmark towards the UK by the mean wind. The smoke over the UK would have been drawn westwards between areas of high and low pressure lying to the north and south of the UK respectively, as seen in figure 6p. Figure 6n2 shows more smoke arriving from the east towards Sweden.

On Saturday 31st March much of the cloud cover over the UK cleared. A haze could be seen over the whole of the UK apart from Scotland (see figures 6q1 and 6q2).

Figures 6r to 6u for the 1st to the 4th April show the smoke continuing to clear from the UK. Clean air, moving in from the north, initially forced the polluted air to the south of the UK before the particulates were gradually drawn out westwards over the Atlantic and air masses reaching the UK became northerly.

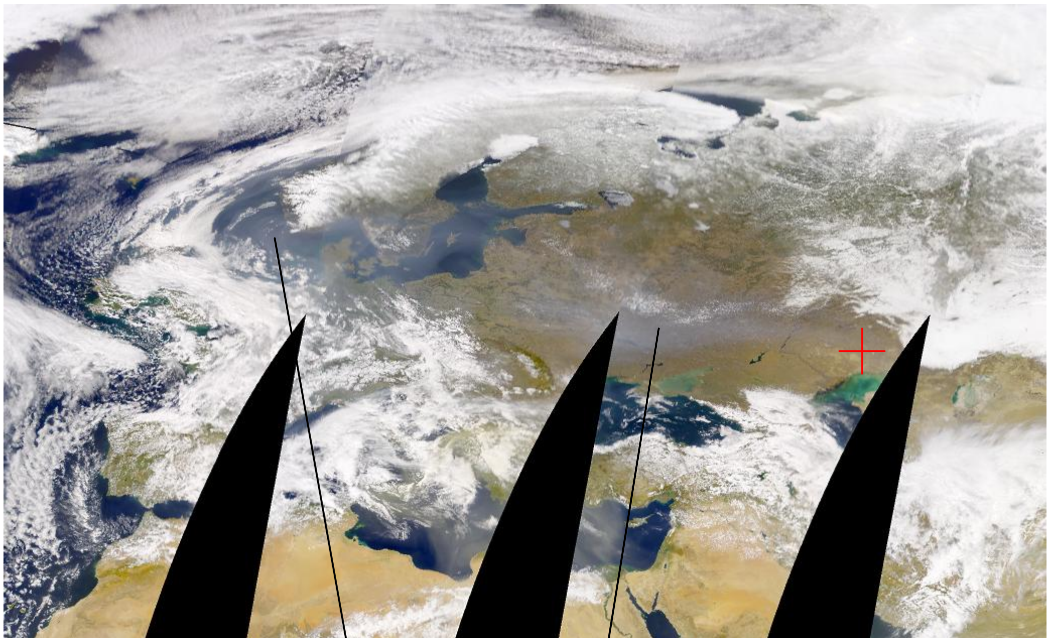


Figure 6l1: 29th March

Figure 6l2: 29th March

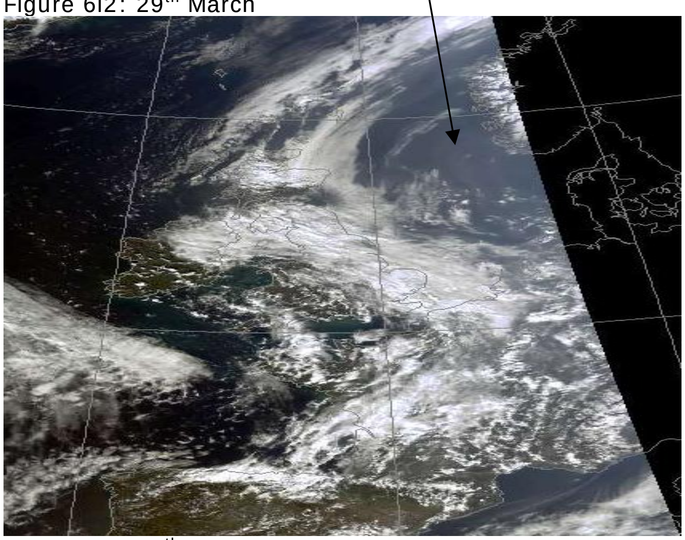


Figure 6l3: 29th March

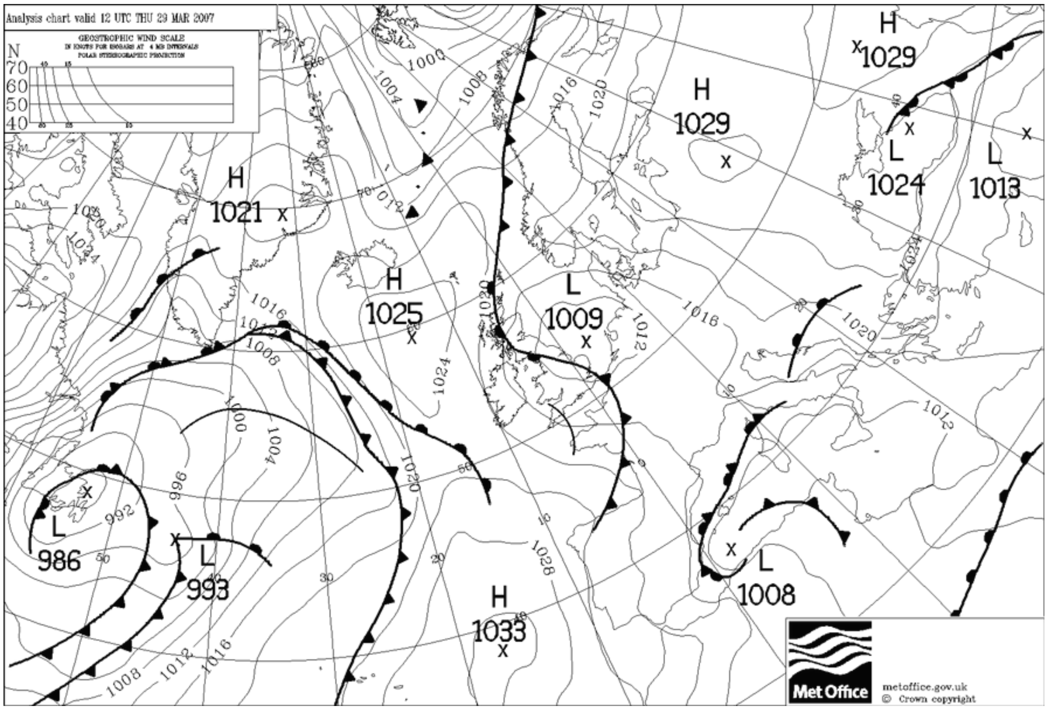


Figure 6m: 12:00 on the 29th

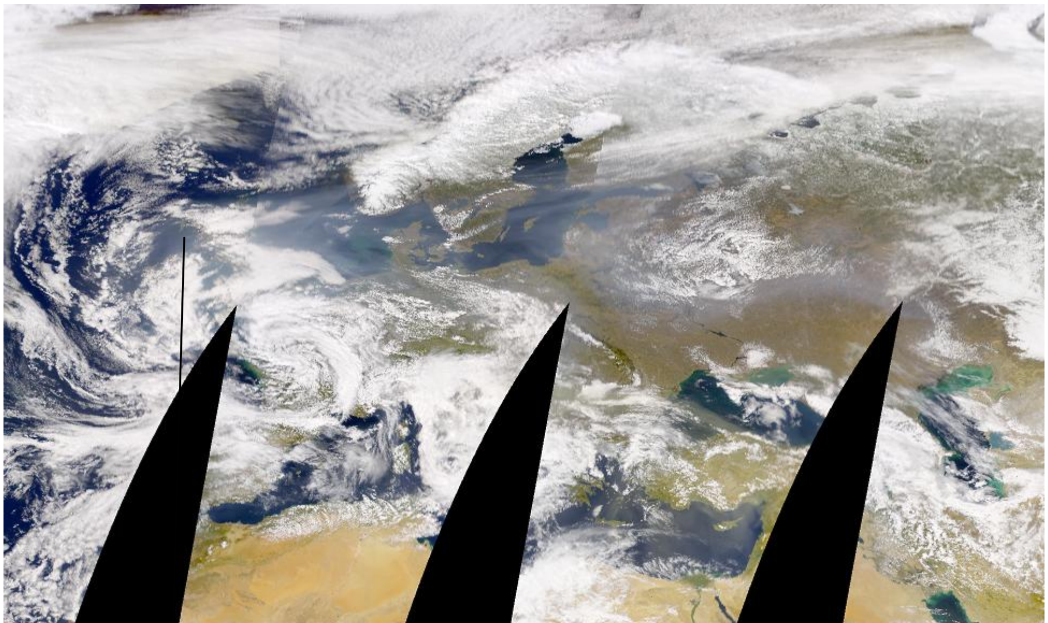


Figure 6n1: 30th March

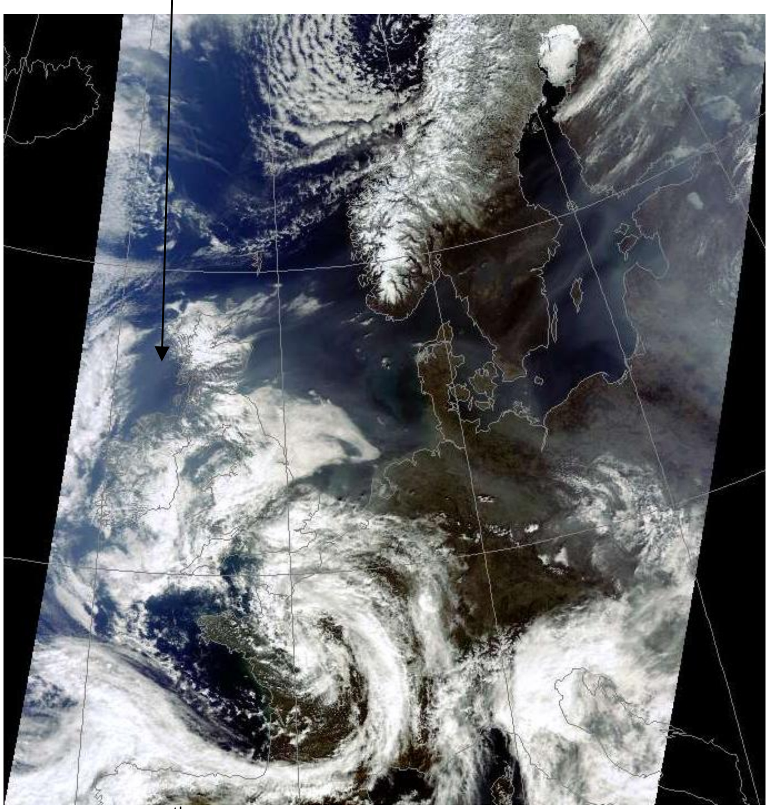


Figure 6n2: 30th March

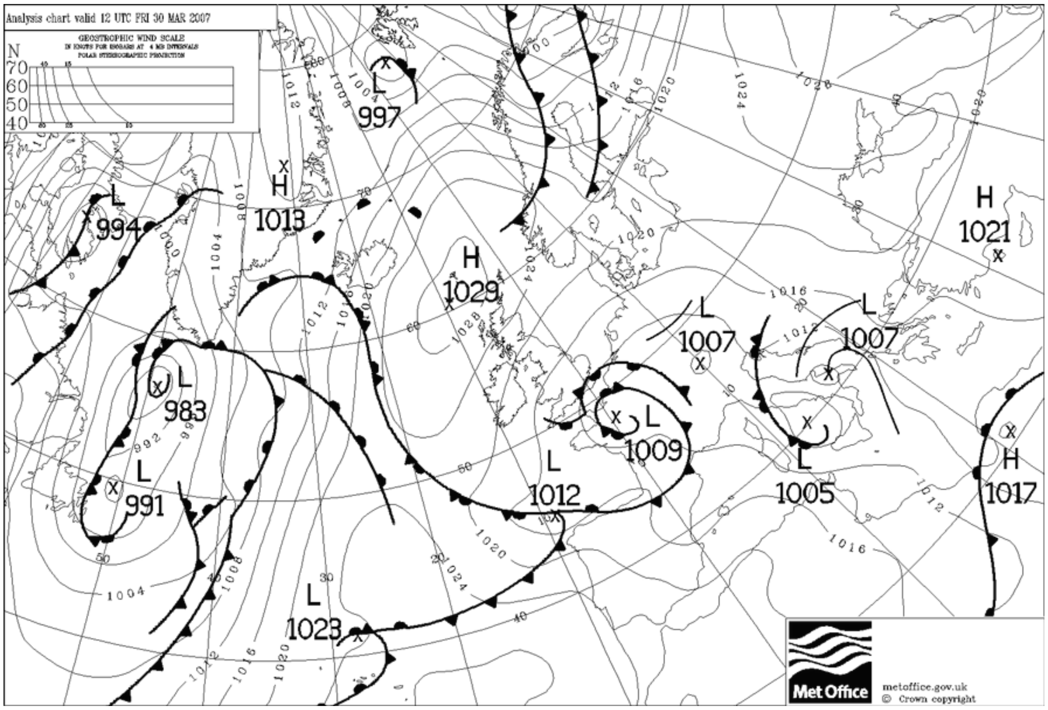


Figure 6p: 12:00 on the 30th

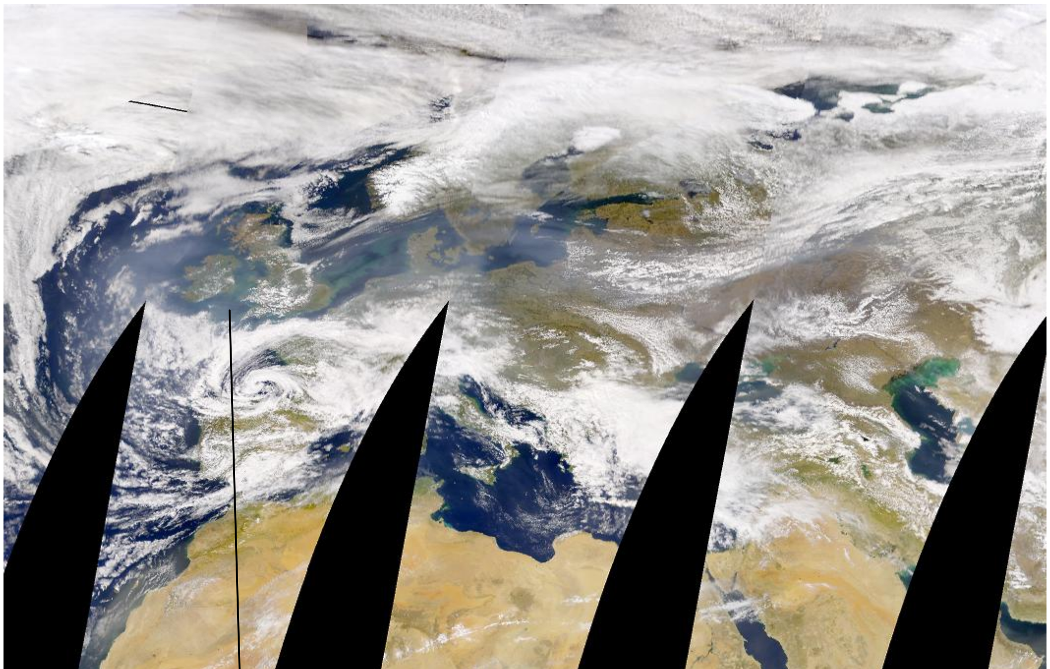


Figure 6q1: 31st March

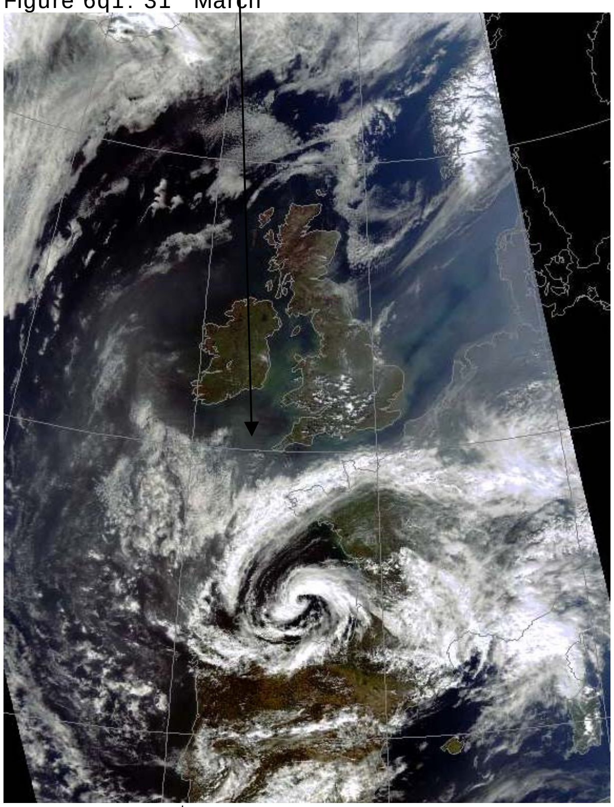


Figure 6q2: 31st March

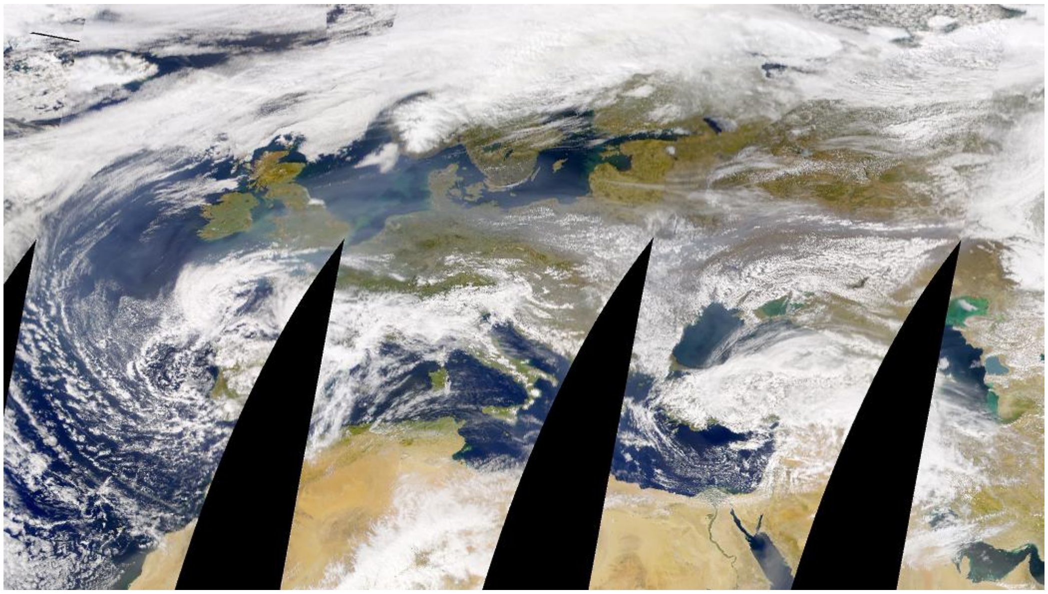


Figure 6r: 1st April

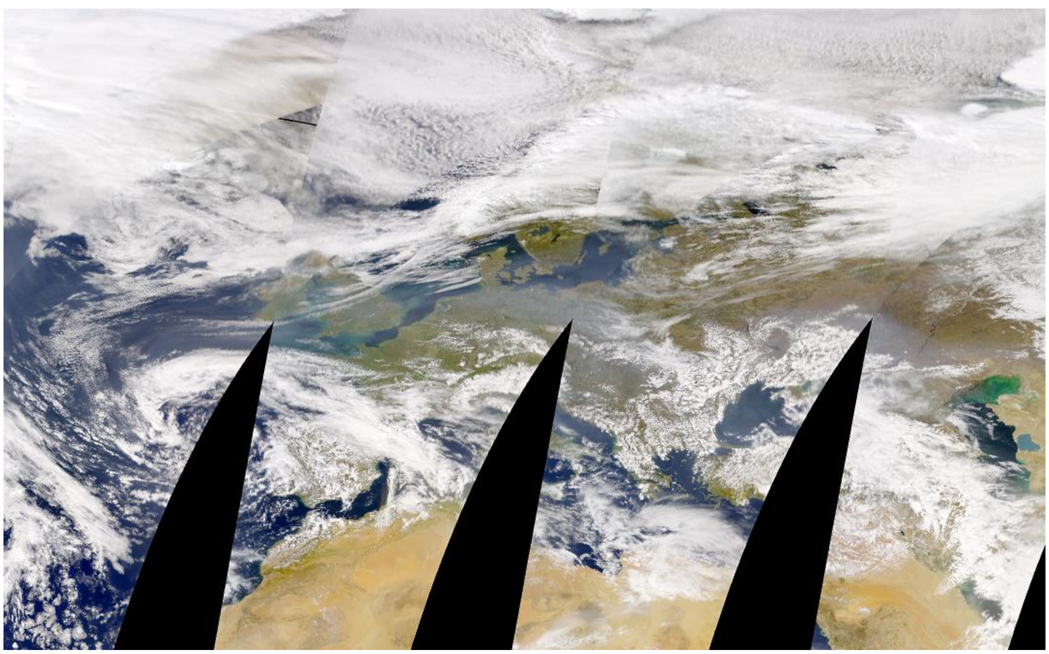


Figure 6s: 2nd April

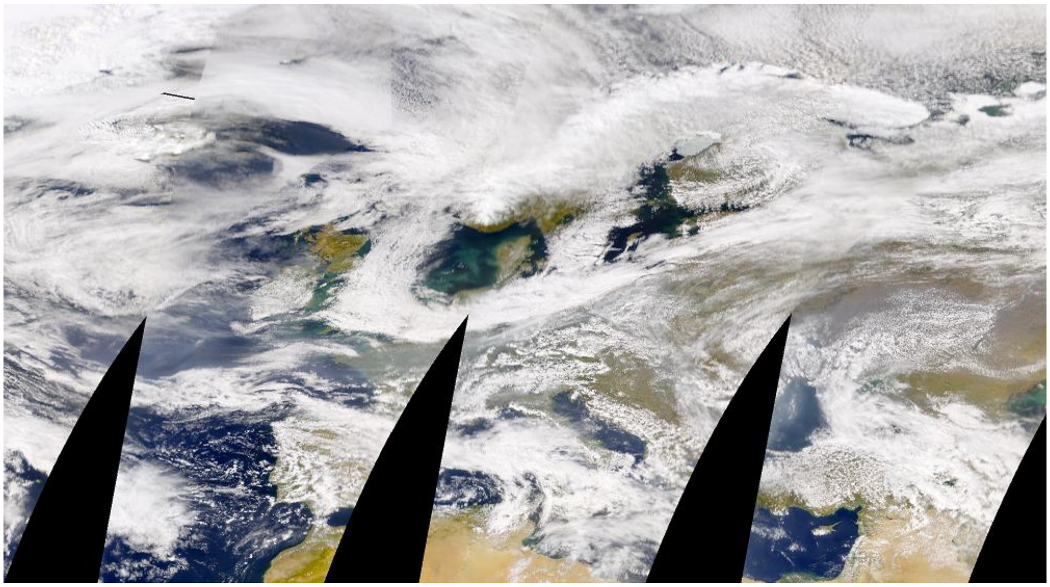


Figure 6t: 3rd April

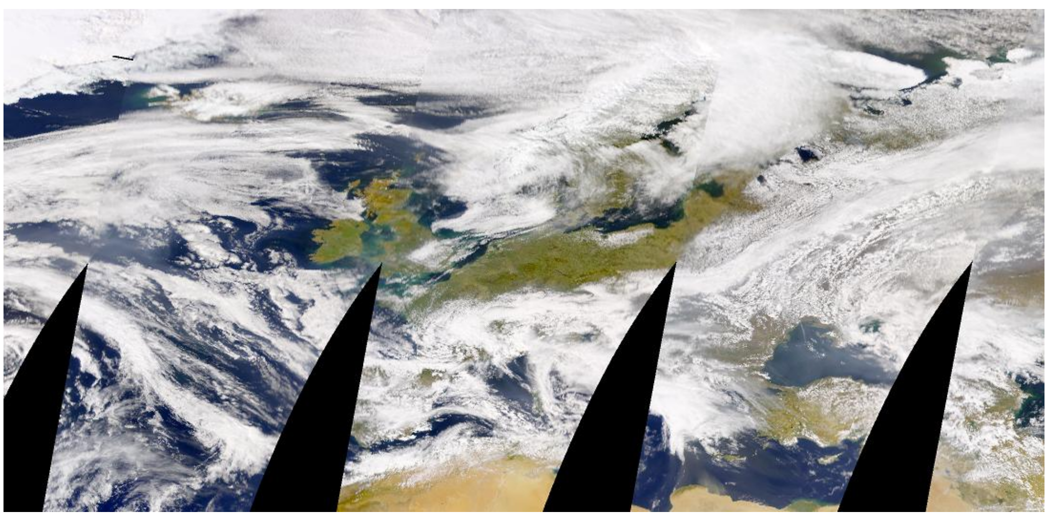


Figure 6u: 4th April

7. Measurements & modelling of the episode over France

The PREV'AIR system was implemented in 2003 upon an initiative by the French Ministry for Ecology and Sustainable Development (MEDD) with the aim of generating and publishing daily air quality forecasts and maps of numerical simulations on different spatial scales. This system also supplies observation maps based on measurements carried out in the French network.

Particulate maps, showing reanalysed forecast concentrations with assimilated observations made in France, as shown in figures 7a to 7l, were obtained from the open access PREV'AIR website (www.prevair.org). The pink areas represent lowest concentrations. The white coloured numbers added to the figures show an indication of the PM_{10} daily averages measured in various parts of France where significant concentrations were experienced. The numbers added to the maps over the south east of England show the gravimetric equivalent PM_{10} daily average range measured at the sites in London Bloomsbury and the rural site near Rochester. The forecast maps presented appear to have been reanalysed based on observations made in France, with sites from the UK not assimilated.

Figures 7a- 7l show a fair agreement between daily averages measured at sites in Northern France and the two sites in the south east of England. The exact position of the sites in Northern France was not available, so allowances should be made for possible localised pollution effects.

The highest levels appear to have been measured in northern-most France throughout the episode, whilst the south of France experienced very little of the episode. Cloud and low pressure was situated over Southern France during most of the episode which is likely to explain why the particulate laden air did not pass further to the south.

Daily averaged PM_{10} levels in the region of 100 $\mu g/m^3$ were measured in northern-most France on the 28^{th} and 29^{th} March, as seen in figures 7e and 7f. The cold front, which brought clear Atlantic air from the west to much of the UK on the 29^{th} March, “broke up” over Northern France on the 30^{th} March which may explain why higher daily averages were experienced in Northern France compared to the south of England on those days. From the 31^{st} March onwards the polluted air was drawn south-westwards towards a low pressure area to the north of Spain. The highest daily averaged particulate levels measured in central-western France during the episode, of up to 55 $\mu g/m^3$, were experienced on the 3^{rd} April when clear air moving southwards from Scandinavia forced the polluted air to travel westwards over central France, as seen in figure 7k.

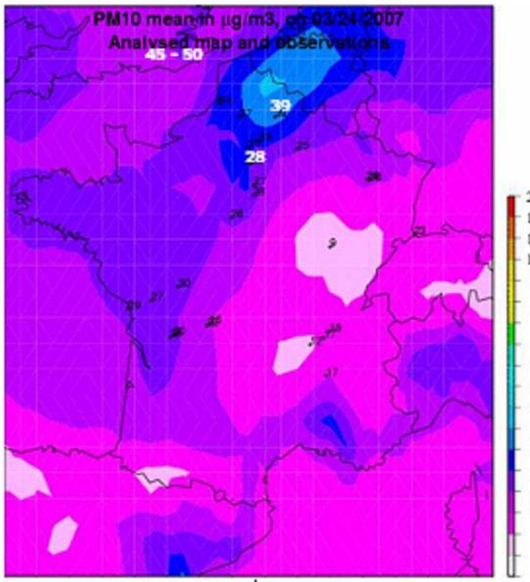


Figure 7a: 24th March

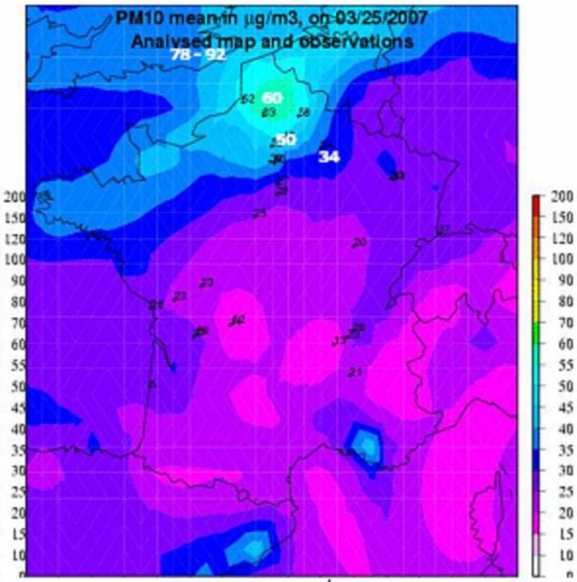


Figure 7b: 25th March

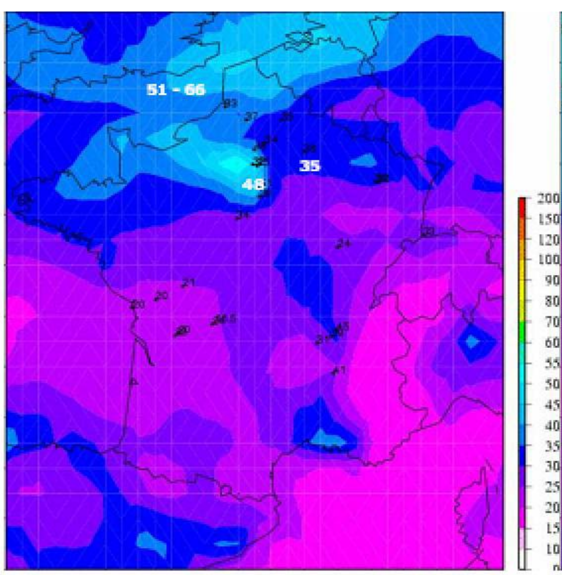


Figure 7c: 26th March

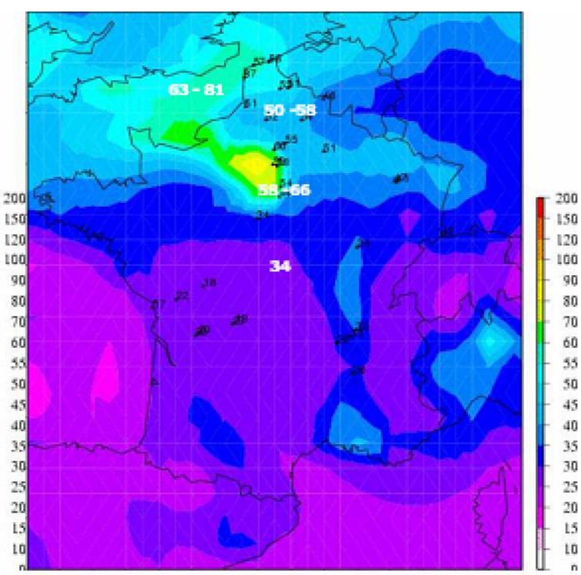


Figure 7d: 27th March

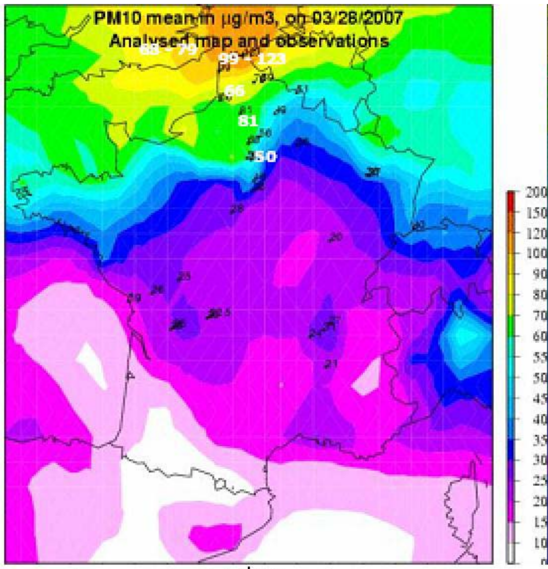


Figure 7e: 28th March

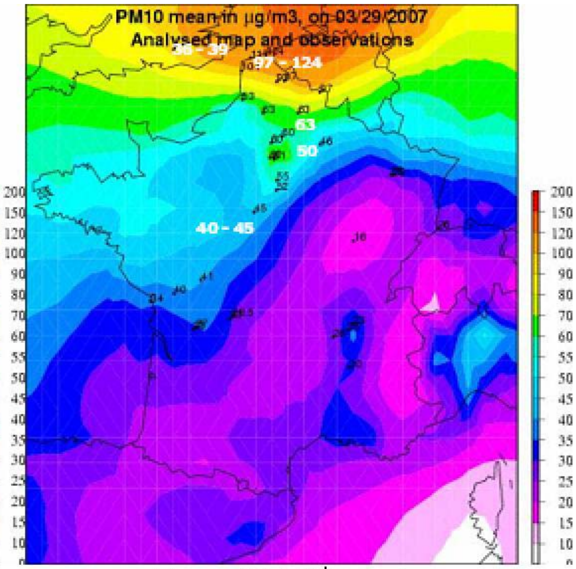


Figure 7f: 29th March

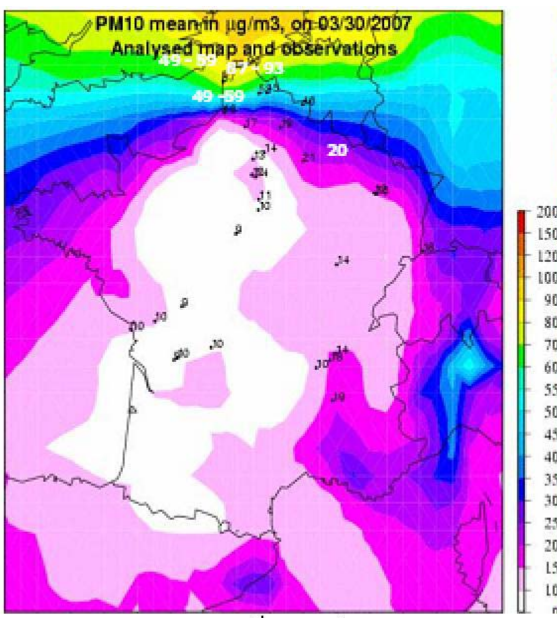


Figure 7g: 30th March

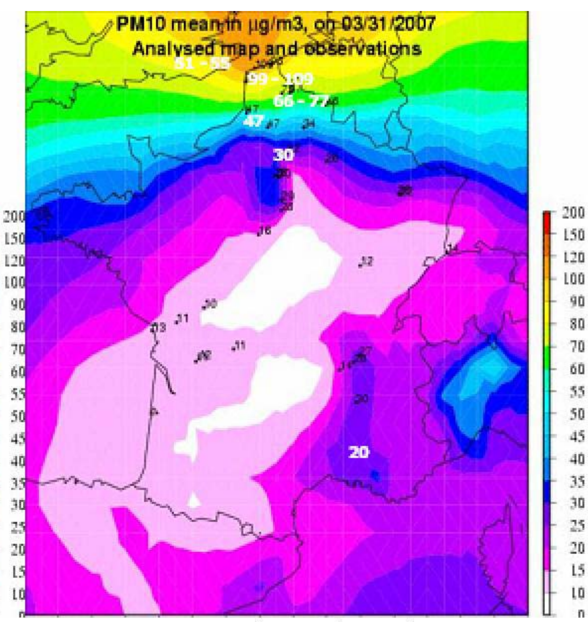


Figure 7h: 31st March

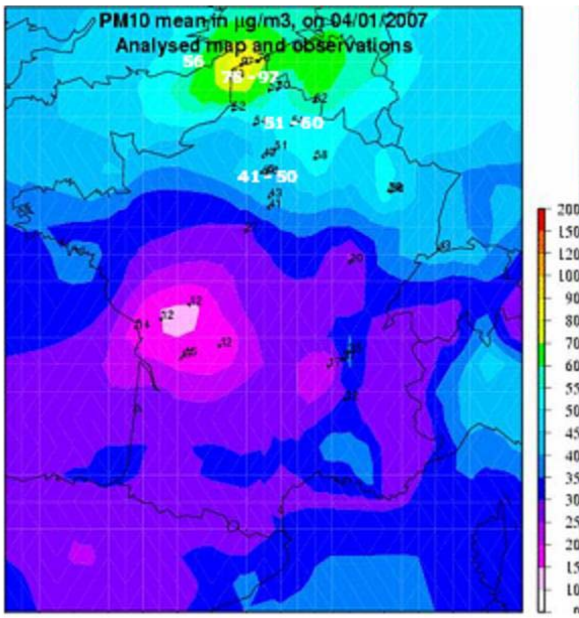


Figure 7i: 1st April

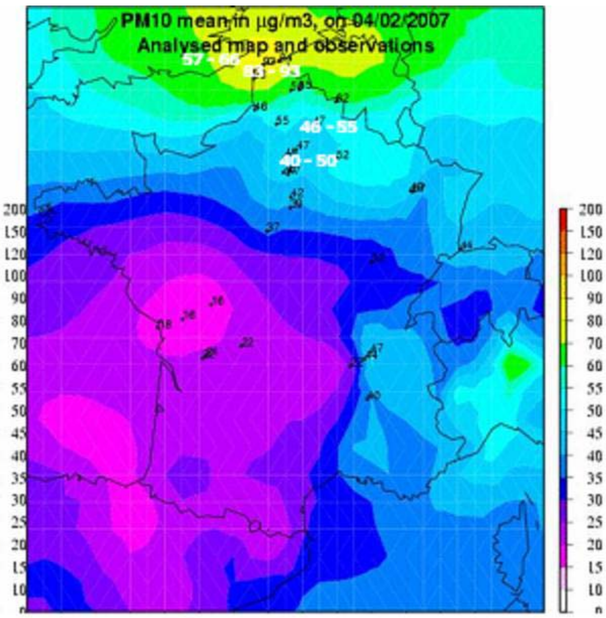


Figure 7j: 2nd April

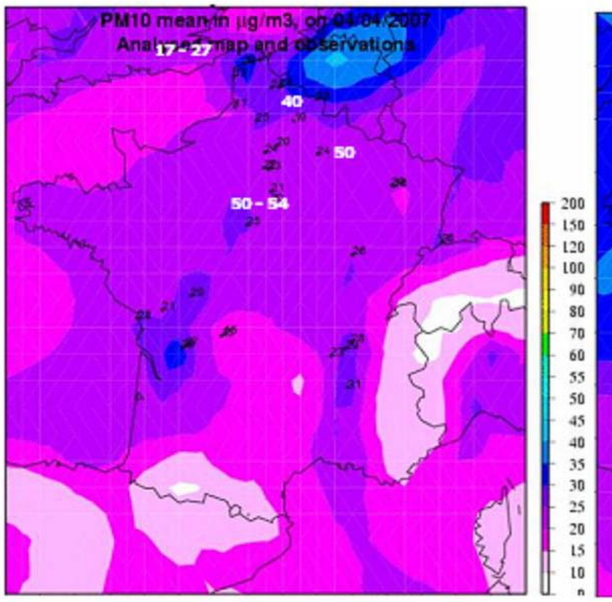


Figure 7k: 3rd April

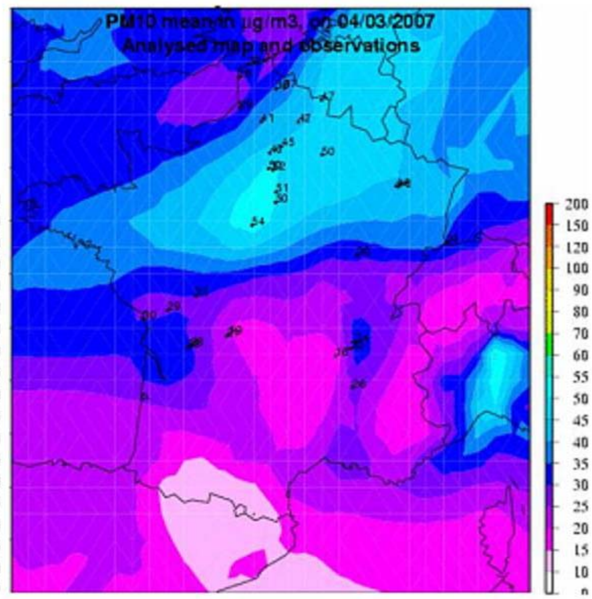


Figure 7l: 4th April

8. Further particle size distribution analysis of measurements during the episode

From our earlier analysis in sections 2-5 of this report AEA and the Met Office concluded that there was a possibility of Saharan dust contributing to at least the first two days of the pollution episode. Here we have carried out further research into the likely distribution of particle sizes in Saharan dust reaching the UK, and whether this fits the observed data.

Typical particle size ratios for PM_{fine} to PM_{coarse} were estimated using reference data found in the book “Atmospheric Chemistry and Physics” (by Seinfeld / Pandis, ISBN-13: 978-0471720188) for various environment types. The following particle diameter fractions were used to represent the coarse and fine PM fractions: $PM_{fine} = PM_{2.5}$ and $PM_{coarse} = PM_{10} - PM_{2.5}$.

Further research data was found in Schütz et al in 1981 (“Saharan dust transport over the North Atlantic Ocean: model calculations and measurements”. Geological Society of America Special Paper, 186, p 87–100), in which the particle size distribution of Saharan dust was measured at various long-range distances from the source. The PM_{coarse} fraction chosen for the analysis of the March 2007 episode was PM_{10} - $PM_{2.5}$ due to significant changes in the concentration of fractions greater than PM_{20} observed by Schütz et al during the long- range transport of Saharan dust. Schütz et al analysed the size distribution of seven particle size fractions up to the 10 micron diameter range, four of which were used in this analysis.

Hourly averaged PM_{fine} : PM_{coarse} ratios were plotted using data from “Osiris” particulate monitors located at Anglesey Llynfaes and Slough Colnbrook sites, as shown in figures 8a and 8b. Figure 8a shows that the particle fraction ratios measured at Slough Colnbrook entered the range of ratios expected for Saharan dust on the afternoon of the 25th and 26th, where the upper range shown on the plot corresponds to the expected ratio for long-range transport of Saharan dust at 5000 km (i.e PM_{fine} : PM_{coarse} = 0.38). As also shown in the figure and concluded earlier in this report, the episode was characterised by a high proportion of the coarser particulate fraction at the onset (i.e. the lower ratios for the 25th and 26th March as shown in figure 8a). From examining the likely air-mass trajectory path from North Africa to the UK, the actual distance of travel for Saharan dust reaching the UK on March 25th is estimated to have been in the range of 3000-4000 km.

The ratios measured at Angelesey Llynfaes also entered the range expected for Saharan dust (i.e a ratio of less than 0.38) on the morning of the 25th for about an hour, which coincided exactly with the onset of the episode. The Saharan dust range was also entered for short periods on the 28th and 29th but may have been due to other particles since these occurred after the period which is considered to have been the episode’s onset.

Ratios associated with the long-range transport of pollution and secondary oxidation products, typically measured at “remote” sites and found at ratios of 3.2 or above, were seen at these sites on the 27th, 28th, 30th and the 31st March, suggesting that the finer fractions measured on those days were likely to have been caused by long-range transport from a non-Saharan source, either secondary aerosols or smoke is hypothesized. The ratio for long-range transport shown in both figures is representative of a typical ratio, as derived from the book “Atmospheric Chemistry and Physics” mentioned earlier in this section.

Various assumptions were made for the analysis, which include:

- The particulates measured during the episode were exclusively caused by long range transport, or that localised pollution did not significantly contribute to the levels measured.
- The density of the particles was the same at all particle diameters.
- The particle size distribution of Saharan dust arriving in the UK from long range transport over Europe is similar to that measured by Schütz et al for long range transport of Saharan dust over the North Atlantic Ocean to the USA.

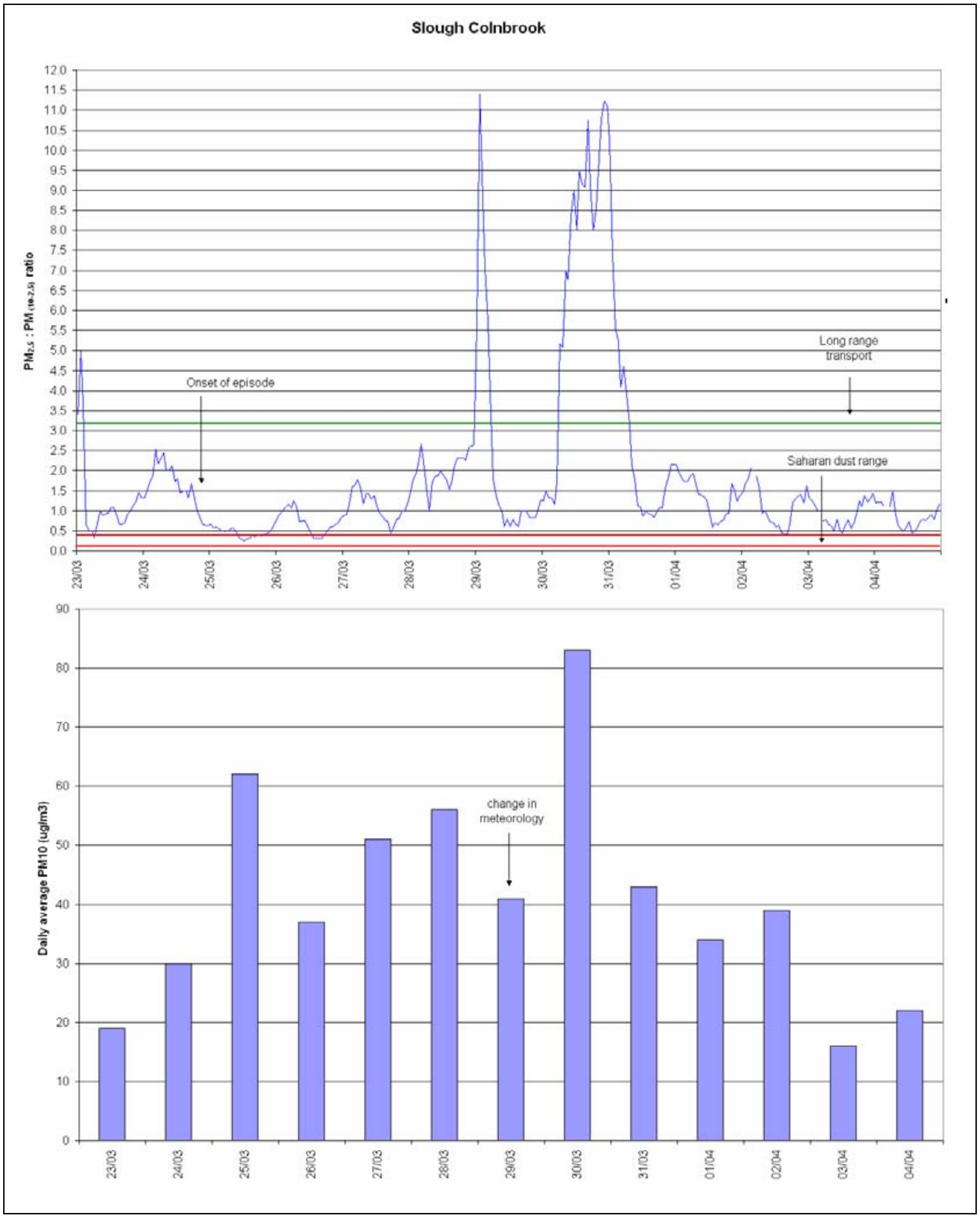


Figure 8a: Particle fraction ratios during the episode at Slough Colnbrook

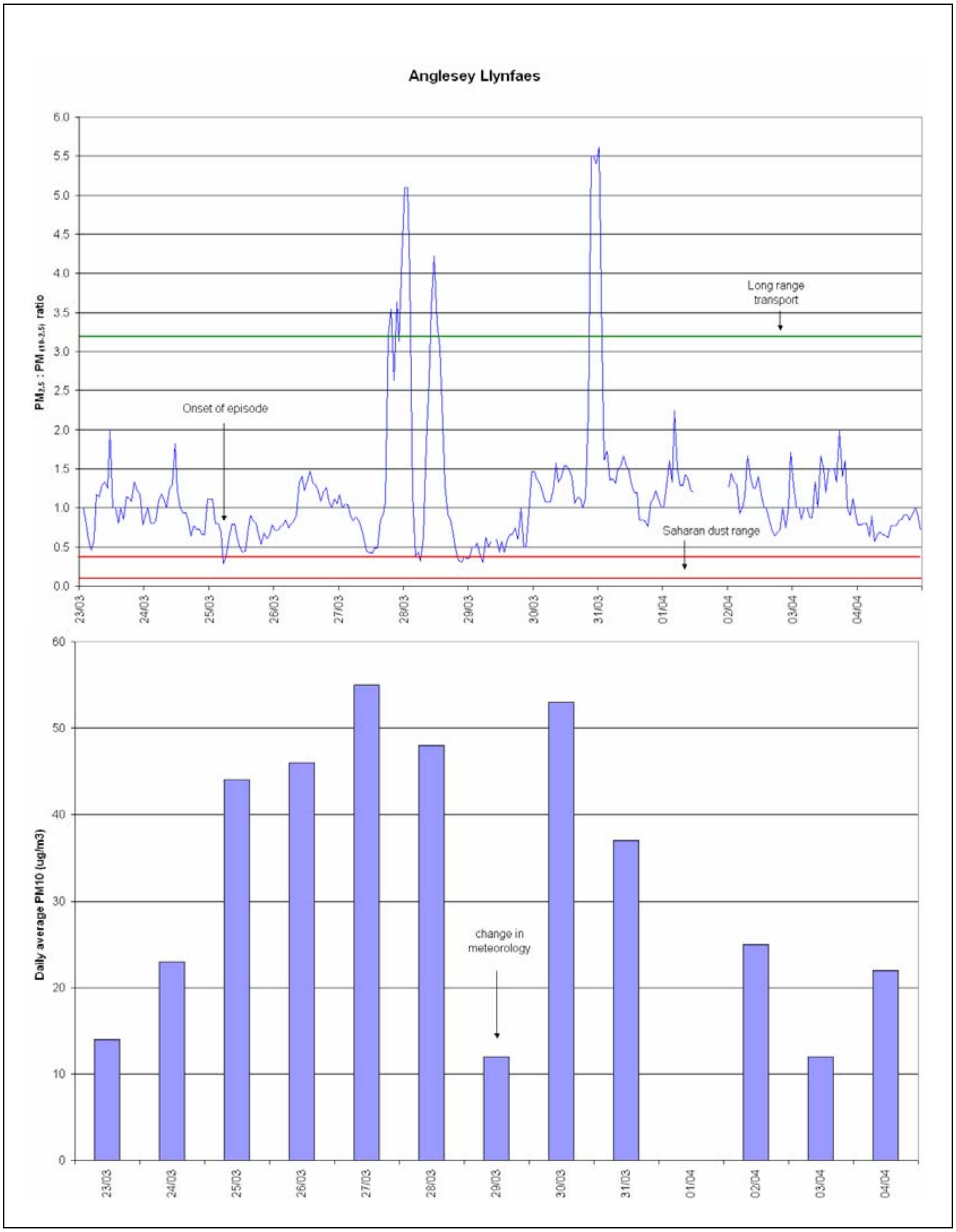


Figure 8b: Particle fraction ratios during the episode at Anglesey Llynfaes

9. Analysis of the relative responses of TEOM and TEOM-FDMS instruments during the episode

Many of the TEOMs in the AURN network are currently being replaced / upgraded to FDMS-TEOMs. The occurrence of the episode provided an opportunity for comparison of the responses of TEOM and FDMS PM_{10} instruments in a real pollution episode situation.

TEOM instruments are real-time particulate mass monitors with a heated inlet temperature of around 50 degrees C. The inlet temperature used ensures that water vapour does not interfere with measurements but also has the additional effect of driving off volatile particulate species prior to measurement. The FDMS-TEOM is a recent modification to this measurement technique in which a lower inlet temperature of 30 degrees C is used and the volatile / non-volatile fractions are measured separately with cycling between the two instrument modes.

An analysis of the data obtained from a TEOM instrument at Birmingham Tyburn and a nearby FDMS instrument at Birmingham Centre has been undertaken. The relative response of the two instruments is analysed as a function of the volatile component measured by the FDMS instrument. The variance between the relative responses is shown in Figure 9a and appeared to be related to the quantity of the volatile fraction measured.

Based on the graphs produced, the TEOM data (multiplied by a nominal factor of 1.3 to allow for loss of the volatile fraction - called conversion to gravimetric equivalent units) tended to over-estimate at lower volatile component concentrations and under-estimate predominantly at values above 10 $\mu g/m^3$ of volatile mass component over the period of the episode.

The average gravimetric TEOM equivalent over-estimation compared to the FDMS instrument during the episode was calculated to be 7 %, suggesting that an average conversion factor of 1.22 would have been most suitable to use during the days of the elevated measurements.

A comparison between AURN TEOM sites and the Reading New Town FDMS site in the south–east of England (Figure 9b) shows a very similar pattern to the Birmingham sites. The FDMS TEOM measured significant amounts of volatile material lost by the older TEOMs. The Birmingham sites were used for the further analysis presented below (figures 9c and 9d) due to their closer proximity to each other. Significant local emissions measured at either site in Birmingham could have had an effect on the data analysed but this does not appear to be the case from viewing the hourly timeseries plots.

An increase in volatile fraction was measured at all FDMS sites across England from the 27th to the 31st March, as illustrated in Figure 9e. This was consistent with secondary particulates transported from Europe to the UK during the working week, with a time delay of approximately one day to reach the UK. Rain or temporary clearance of the particulate laden air in many UK regions on the 29th March had a dramatic effect on lowering the mass concentration (MC) levels of all components of the airborne particulate matter.

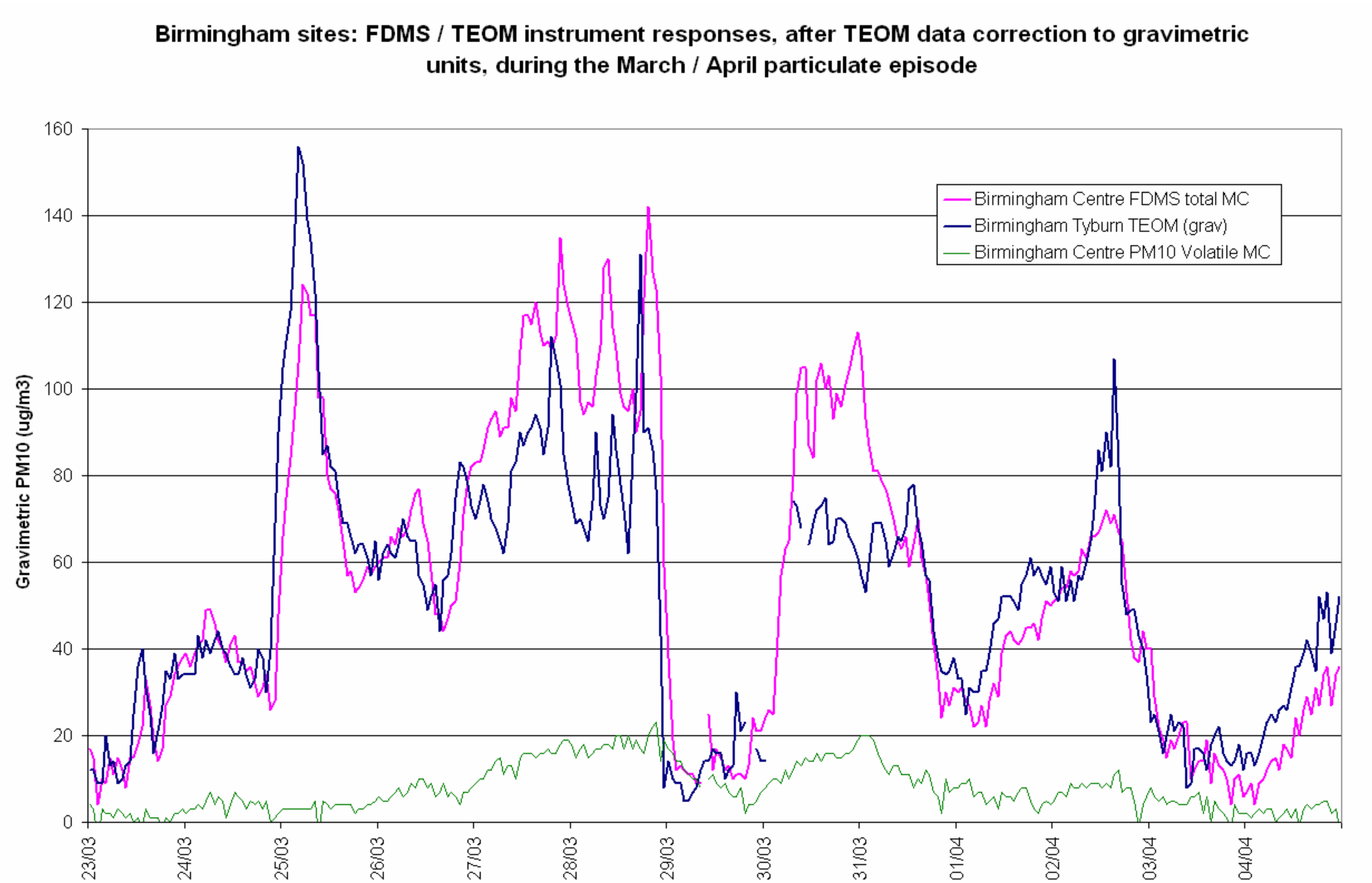


Figure 9a: The relative response of TEOM and FDMS instruments in terms of hourly averages.

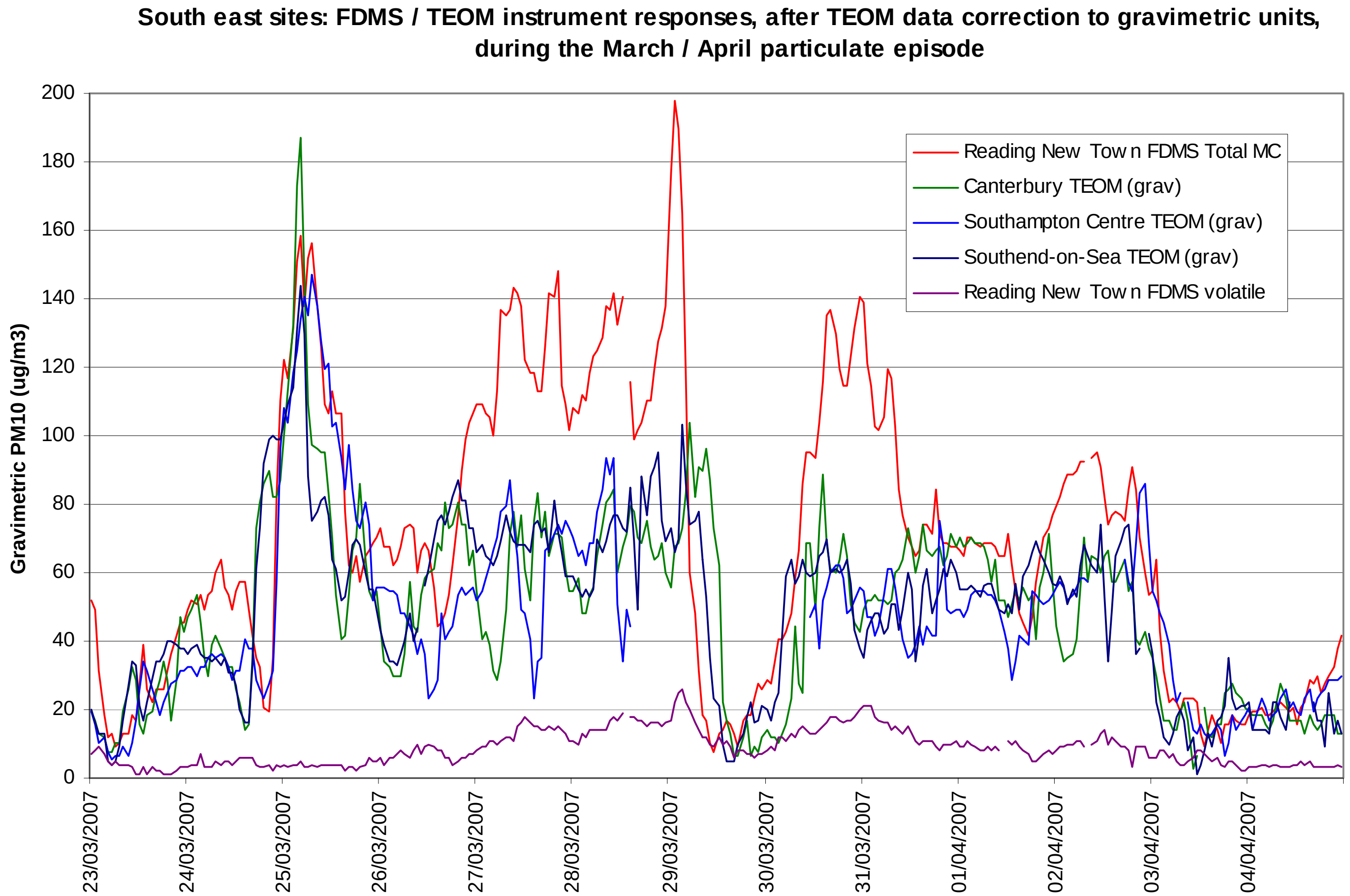


Figure 9b: The relative response of TEOM and FDMS instruments in terms of hourly averages for sites in the south east.

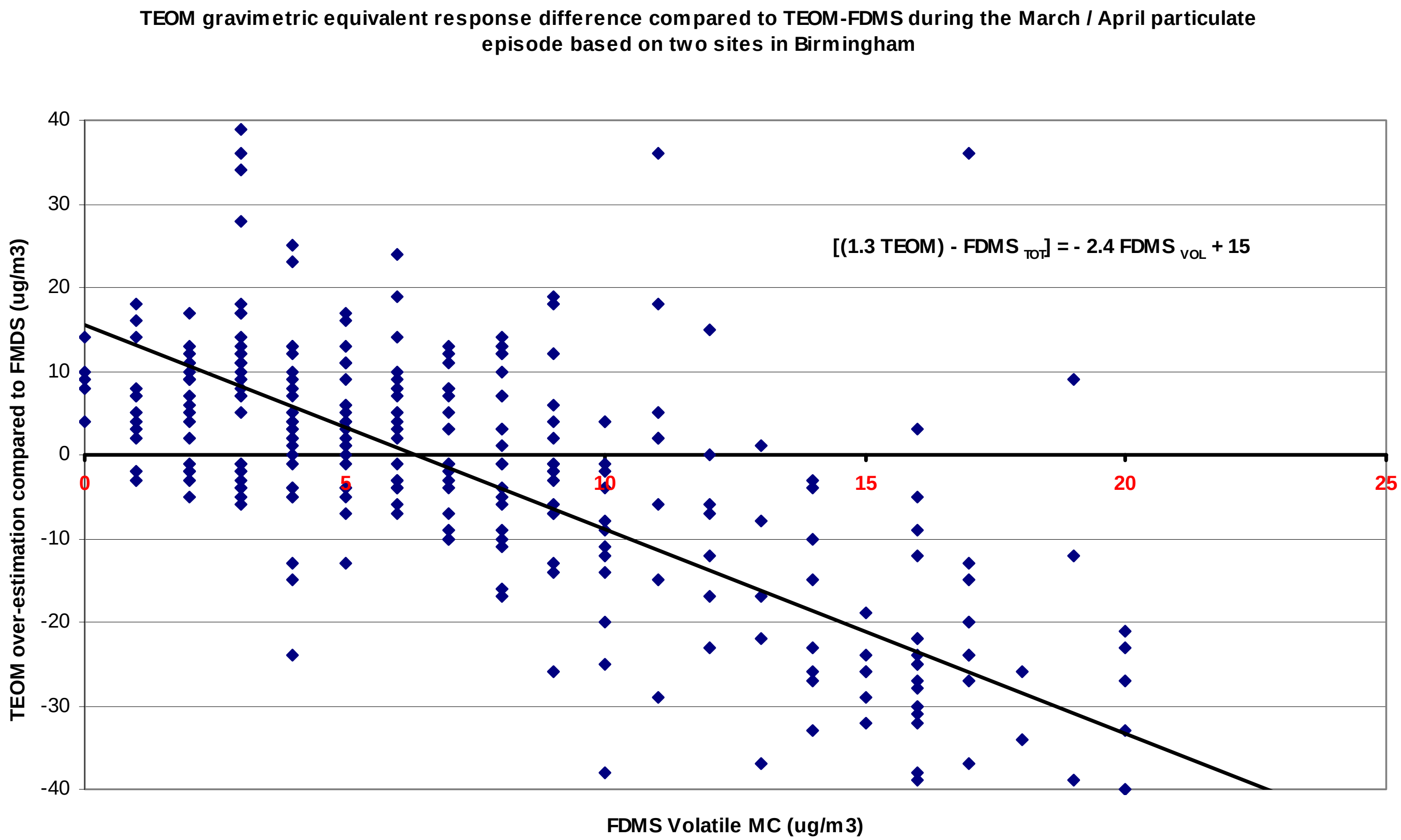


Figure 9c: A comparison of the response of TEOM and FDMS instruments as a function of volatile mass component measured.

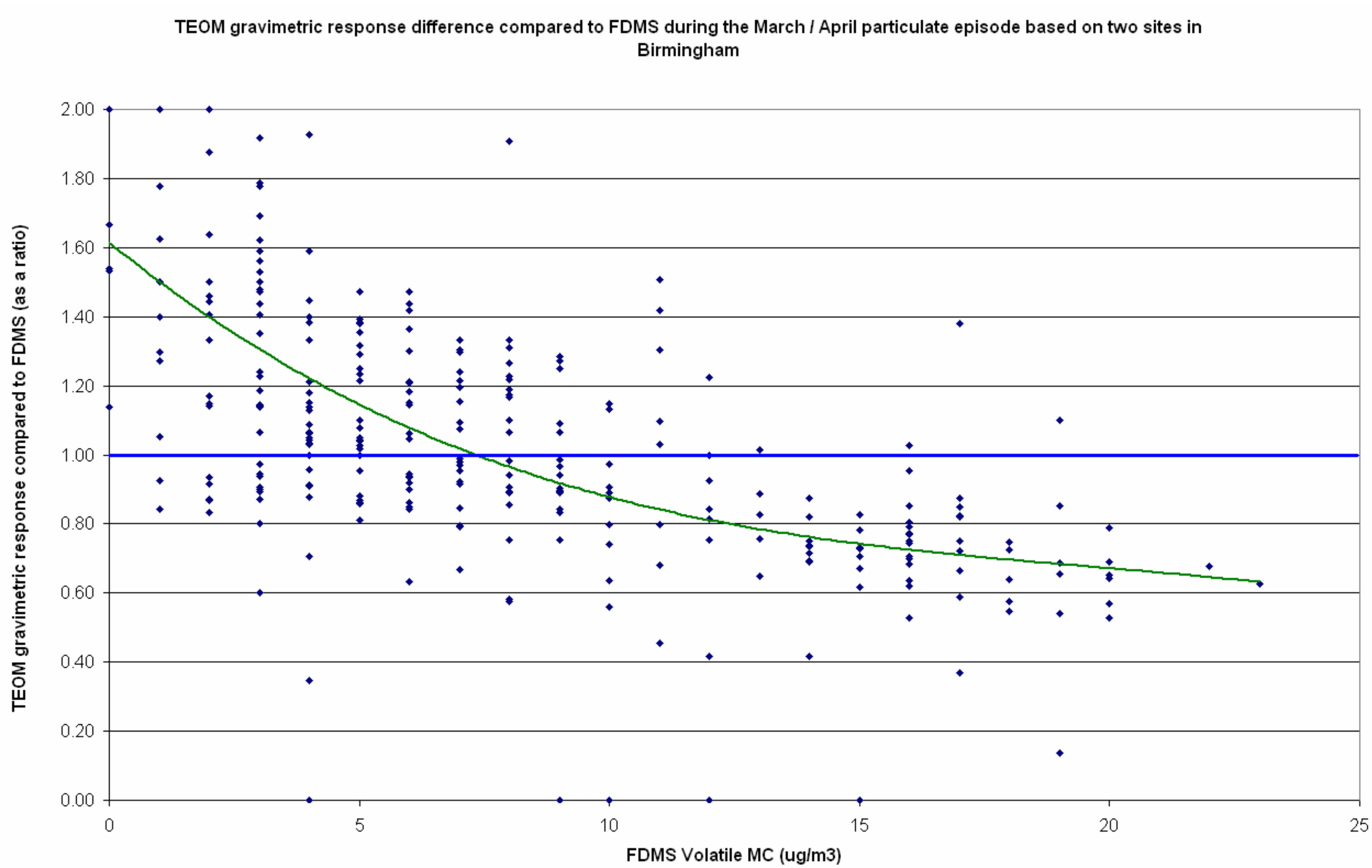


Figure 9d: The relative response of TEOM and FDMS instruments as a function of volatile mass component measured.

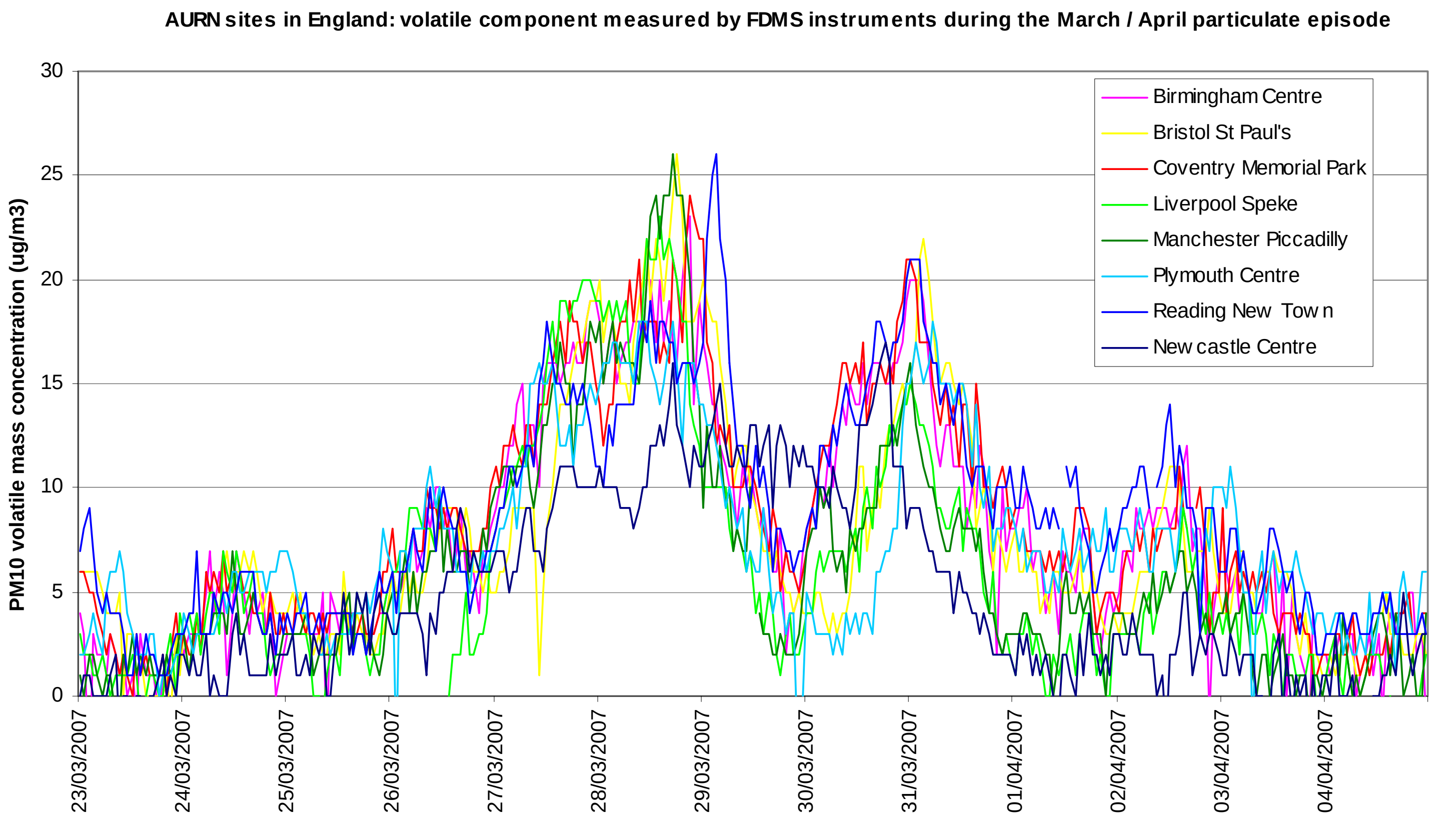


Figure 9e: The volatile component of PM_{10} measured, in terms of hourly averages, for sites in England.

10. Conclusions

The main features of the late March/early April 2007 particulate episode may be summarised as follows:

Air sourced from the Ukraine and western Russia and often passing over northern Europe contained a cloud of particulates for at least 7 days, between approximately 25th March and 2nd April.

Dust from sandstorms in North Africa and Jordan/Syria, leading up to the event, may have contributed to the particulates reaching the UK during the episode, especially during the early stages, as shown by both satellite imagery and modelling studies.

The satellite imagery captured clearly shows smoke issuing from the vicinity of the Ukraine with easterly transport of the particulates.

FDMS data indicate that the air reaching the UK during the mid and late stages of the episode is likely to have contained secondary particulates formed from emissions across continental Europe.

The particulate laden air is therefore thought to have been the result of long range transport from fires in Russia and the Ukraine, combined with a contribution of European secondary PM_{10} pollution and also dust from sandstorms in the region of North Africa.

Acknowledgements

Thanks to the Met Office for supplying weather charts to cover the period of the pollution episode. Thanks to the NERC Satellite Receiving Station at Dundee University in Scotland, NASA/GSFC MODIS Rapid Response, the MSG service, the SeaWiFS Project: NASA/Goddard/GeoEYE and EUmetsat for allowing publication of the satellite images shown in this report. Thanks to the PREV'AIR system for allowing publication of the particulate maps found in this report and to wikipedia.org for allowing the use of a copyright-free image available on their website. Thanks to Slough Borough, Norwich City and the Isle of Anglesey County Councils for allowing the use of their air quality monitoring data used for comparisons within this report and also to Horsham District Council for supplying a summary of ground level dust fall observations made by the public.

APPENDIX – UK AIR POLLUTION INDEX

Old Banding	Index	Ozone 8-hourly / Hourly mean		Nitrogen Dioxide Hourly Mean		Sulphur Dioxide 15-Minute Mean		Carbon Monoxide 8-Hour Mean		PM_{10} Particles 24-Hour Mean
		μgm^{-3}	ppb	μgm^{-3}	ppb	μgm^{-3}	ppb	mgm^{-3}	ppm	gravimetric μgm^{-3}
LOW										
	1	0-32	0-16	0-95	0-49	0-88	0-32	0-3.8	0.0-3.2	0-21
	2	33-66	17-32	96-190	50-99	89-176	33-66	3.9-7.6	3.3-6.6	22-42
	3	67-99	33-49	191-286	100-149	177-265	67-99	7.7-11.5	6.7-9.9	43-64
MODERATE										
	4	100-126	50-62	287-381	150-199	266-354	100-132	11.6-13.4	10.0-11.5	65-74
	5	127-152	63-76	382–477	200-249	355-442	133-166	13.5-15.4	11.6-13.2	75-86
	6	153-179	77-89	478-572	250-299	443-531	167-199	15.5-17.3	13.3-14.9	87-96
HIGH										
	7	180-239	90-119	573-635	300-332	532-708	200-266	17.4-19.2	15.0-16.5	97-107
	8	240-299	120-149	636-700	333-366	709-886	267-332	19.3-21.2	16.6-18.2	108-118
	9	300-359	150-179	701-763	367-399	887-1063	333-399	21.3-23.1	18.3-19.9	119-129
VERY HIGH										
	10	$\geq 360\ \mu gm^{-3}$	$\geq$ 180 ppb	$\geq 764\ \mu gm^{-3}$	$\geq$ 400 ppb	$\geq 1064\ \mu gm^{-3}$	$\geq$ 400 ppb	$\geq 23.2\ mgm^{-3}$	$\geq$ 20 ppm	$\geq 130\ \mu gm^{-3}$