

NRPB-R316

Atmospheric Dispersion Modelling  
Liaison Committee

Annual Report 1997/98

NRPB-R316



National Radiological Protection Board

**MAIN TEXT**

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**ANNEX – Portability of Weather Data for Dispersion Calculations**

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This report was produced by the National Radiological Protection Board for the Atmospheric Dispersion Modelling Liaison Committee.

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The National Radiological Protection Board was established by the Radiological Protection Act 1970. It is responsible for conducting research and providing advice and services for protection against both ionising and non-ionising radiations.

Any questions relating to this document should be addressed to the Information Office, National Radiological Protection Board, Chilton, Didcot, Oxfordshire OX11 0RQ. E-mail: [information@nrpb.org.uk](mailto:information@nrpb.org.uk).

Website: [www.nrpb.org.uk](http://www.nrpb.org.uk)

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**Atmospheric Dispersion Modelling  
Liaison Committee**

**Annual Report 1997/98**

**National Radiological Protection Board  
Chilton  
Didcot  
Oxon OX11 0RQ**

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**This NRPB report reflects understanding and evaluation of the current scientific evidence as presented and referenced in this document.**



## **Preface**

In 1977 a meeting of representatives of government departments, utilities and research organisations was held to discuss methods of calculation of atmospheric dispersion for radioactive releases. Those present agreed on the need for a review of recent developments in atmospheric dispersion modelling, and a Working Group was formed. Those present at the meeting formed an informal Steering Committee, that subsequently became the UK Atmospheric Dispersion Modelling Liaison Committee. That Committee operated for a number of years. Members of the Working Group worked voluntarily and produced a series of reports. A workshop on dispersion at low wind speeds was also held, but its proceedings were never published.

The Committee has now been reorganised and has adopted terms of reference. The organisations represented on the Committee, and the terms of reference adopted, are given in this report. The organisations represented on the Committee pay a small annual subscription. The money thus raised is used to fund reviews on topics agreed by the Committee, and to support in part its secretariat, provided by NRPB. The new arrangements came into place for the start of the 1995/96 financial year. This report describes the third year in which the Committee has operated under the new arrangements, and during which it placed one contract for a review of the representativity of weather data for dispersion calculations. The technical specification for this contract is given in this report, and the contract report is attached as an annex to this report. The Committee funded five studies in previous years; they are described in its earlier annual reports.

The Committee intends to place further contracts in future years and would like to hear from those interested in tendering for such contracts. They should contact the Secretary:

**Mr J G Smith**  
**National Radiological Protection Board**  
**Chilton**  
**Didcot**  
**Oxon OX11 0RQ**

**E-mail: [justin.smith@nrpb.org.uk](mailto:justin.smith@nrpb.org.uk)**



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# Atmospheric Dispersion Modelling Liaison Committee

## 1 Organisations represented on the Committee

Atomic Weapons Establishment, Aldermaston  
British Nuclear Fuels plc  
Department of the Environment Northern Ireland  
Environment Agency  
Health and Safety Executive  
    Major Hazards Assessment Unit  
    Nuclear Installations Inspectorate  
Magnox Electric  
Ministry of Agriculture, Fisheries and Food  
Meteorological Office  
National Nuclear Corporation  
National Radiological Protection Board  
Nycomed Amersham plc  
Royal Naval College, Greenwich  
Rolls Royce and Associates plc  
Scottish Nuclear  
Scottish Office (SEPA)  
Urenco (Capenhurst)  
Westlakes Research Institute

The Chairman and Secretary are provided by NRPB.

## 2 Terms of reference

- 1 To review current understanding of atmospheric dispersion and related phenomena and to identify suitable models for application primarily in authorisation or licensing, in the context of discharges to atmosphere resulting from nuclear industry activities.
- 2 The Committee shall consist of representatives of government departments, government agencies and primarily the nuclear industry. Each organisation represented on the Committee shall pay an annual membership fee of £1000.
- 3 The Committee will consider selected topics. These should be selected following discussion and provisional agreement at meetings of the Committee, followed by confirmation after the meeting. Where possible, it will produce reports describing suitable models for that topic. These will reflect either the views of an Expert Working Group appointed by the Committee or the outcome of a workshop organised on behalf of the Committee. The Working Group will determine who should be invited to speak at workshops, and to subsequently review their outcome and identify suitable models.
- 4 The money raised from membership fees and registration fees for the workshops will be used to support the Working Group, the drafting of reports, and any other matters which the Committee may decide.

### **3 Reports of the Committee and its earlier Working Group on Atmospheric Dispersion**

Clarke, R H (1979). The first report of a Working Group on Atmospheric Dispersion: a model for short and medium range dispersion of radionuclides released to the atmosphere. Harwell, NRPB-R91.

Jones, J A (1981). The second report of a Working Group on Atmospheric Dispersion: a procedure to include deposition in the model for short and medium range dispersion of radionuclides. Chilton, NRPB-R122.

Jones, J A (1981). The third report of a Working Group on Atmospheric Dispersion: the estimation of long range dispersion and deposition of continuous releases of radionuclides to atmosphere. Chilton, NRPB-R123.

Jones, J A (1981). The fourth report of a Working Group on Atmospheric Dispersion: a model for long range atmospheric dispersion of radionuclides released over a short period. Chilton, NRPB-R124.

Jones, J A (1983). The fifth report of a Working Group on Atmospheric Dispersion: models to allow for the effects of coastal sites, plume rise and buildings on dispersion of radionuclides and guidance on the value of deposition velocity and washout coefficients. Chilton, NRPB-R157.

Jones, J A (1986). The sixth report of a Working Group on Atmospheric Dispersion: modelling wet deposition from a short release. Chilton, NRPB-R198.

Jones, J A (1986). The seventh report of a Working Group on Atmospheric Dispersion: the uncertainty in dispersion estimates obtained from the Working Group models. Chilton, NRPB-R199.

Atmospheric Dispersion Modelling Liaison Committee (1997). Annual Report 1995/96. Chilton, NRPB-R292.

*Includes annexes:*

- Atmospheric dispersion at low wind speed
- Application of computational fluid dynamics codes to near-field atmospheric dispersion
- Rise of a buoyant plume from a building wake

Atmospheric Dispersion Modelling Liaison Committee (1998). Annual Report 1996/97. Chilton, NRPB-R302.

*Includes annexes:*

- Atmospheric dispersion at low wind speed
- Review of models for calculating air concentrations when plumes impinge on buildings or the ground

### **4 Specification for the technical annex**

#### **Portability of weather data for dispersion calculations**

This work was undertaken following discussions between the Committee and the Meteorological Office. The following is the final proposal from the Meteorological Office, which was accepted by the Committee.

In this proposal the following two questions are addressed.

- To what extent are weather data from one site able to represent dispersion at another?
- Is it adequate to have on-site measurements of wind with other data obtained remotely, in order to estimate dispersion?

The basic method chosen is to run the ADMS dispersion model in climate mode at several sites, and to compare the estimates of concentration. A map of the sites which are to be considered is attached. (*Note* – this identified 18 sites in central and southern England.) The dispersion of material from a typical ‘ground’ source [a 10 m stack emitting gas at low temperature (40 C)] and an elevated buoyant source [a 130 m stack emitting gas at high temperature (150 C)] will be used in the comparison. It is assumed that there is no complication from buildings or local topography.

The annual mean and 99th percentile concentration field out to 10 km from the source will be found using five years of weather data (hourly values of temperature, wind speed and direction at 10 m and cloud cover) for the same period at each station. The results will be presented as maps of concentration. The two estimates of concentration at a site (ie one obtained from weather data at the site and the other from weather data from another site) will be compared.

#### **Comparison for a group of sites**

*Eighteen sites will be used which have a complete set of weather data for a common five-year period. All these sites are in a square of size 260 km × 260 km, and they are fairly evenly distributed in the square. Two sites are on the coast and two are within a few kilometres of the coast. Annual mean and 99th percentile concentrations will be calculated at the sites and compared with each other. A test will be made for seasonal and day/night differences by calculating the mean concentrations in the winter months (December–February) and the summer months (June–August) for the daytime and the night-time hours. The aim is to find how the accuracy of the dispersion estimates varies with distance, the time of year and the time of day for the two types of source.*

#### **Combination of on-site and remote-site data**

*In this test a comparison will be made between the use of on-site wind data combined with remote-site cloud data and all on-site data. One test will be with inland sites (Benson, Heathrow and Gatwick) and a second with a coastal pair (Hurn and Portland). For the inland comparison the wind information at Heathrow will be combined with the cloud data from Benson and Gatwick in turn. The concentration fields which are obtained with the combined datasets at Heathrow will be compared with concentrations using the full set of weather data from Heathrow. In the case of the coastal pair the wind data at Portland will be combined with cloud data from Hurn and the estimates of dispersion using this combined weather dataset will be compared with concentrations made using the full set of data from Portland.*

The final contract report from this work is attached as an annex.



# ANNEX

## Portability of Weather Data for Dispersion Calculations

M N HOUGH AND N NELSON  
THE METEOROLOGICAL OFFICE

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## Summary

An attempt is made to show how well dispersion at a site can be estimated using weather data from nearby sites. The method used is to calculate the dispersion of a buoyant release from a 130 m stack (a typical power station source) and a weakly buoyant release from a 10 m stack (a typical factory source) at a network of sites and to compare the estimates with each other. The ADMS model version 2.11 was used for the dispersion estimates. The study was split into Part A which compared a wide network of sites at long timescales and Part B which is for three sites at shorter timescales, and compares how well a combination of wind data at a remote site with other weather data at the site of dispersion can estimate concentrations.

In Part A the site network consists of 17 sites covering much of lowland England and the surface concentrations were expressed as the spatial peak of the mean and 99th percentile for the five-year period from 1987 to 1991. A comparison of the concentrations showed that there was no systematic change with distance from a site and that the ratios of the peak : mean and 99th percentile concentrations for the sites were larger for the 130 m stack than for the 10 m stack for the whole five-year period and for summer daytime and winter by day or night. When plotted against mean windspeed the peak mean and 99th percentile concentrations were found to decrease with increasing wind speed (130 m stack) but to increase for the 10 m stack. It was concluded that reasonable estimates of concentration can be made at a site provided that the station which provides the weather data has nearly the same annual mean wind speed as the site for which dispersion estimates are required.

Part B is a study of three sites in the London area (Stansted, Gatwick and Heathrow) for June to August in 1992. The wind data at Stansted or Gatwick were combined with cloud and temperature data at Heathrow and the estimates of concentration from the 130 and 10 m stacks were compared with the concentrations calculated using the full set of weather data at Heathrow. The calculations of mean and 99th percentile concentration were made for the whole three-month period and also for consecutive four-day periods and the spatial peak of the mean and 99th percentile were found. For the whole three months it was found that the use of Stansted or Gatwick winds at Heathrow resulted in an overestimate of the concentrations at Heathrow except for the 99th percentile results for the short stack. The results for the four-day periods showed that less than half of the four-day periods which used combined weather data gave an estimate of concentration at Heathrow which was within 10% of the true value. It is concluded that to estimate concentrations over a period of a few hours or days then the site for the wind data should be close to the site of dispersion and with a similar topographical setting and roughness length; alternatively, the wind data can be corrected for roughness length differences.



# PART A

## Comparison for a Group of Sites

### 1 Introduction

When dispersion estimates are made using weather data in a model concerns are sometimes raised as to how well the weather data represents the site of interest. The usual approach is to take the nearest site which has a similar altitude and topographical setting, although usually there is little choice. In much of central and southern England the number of stations which have hourly data on wind speed, wind direction and cloud cover (the minimum weather information needed for dispersion estimates) which are for 24 hours per day and have several years of unbroken record is not large. One station might be expected to represent 5000 km<sup>2</sup> or more in many areas. The situation is worse in northern England and in Scotland.

The study of the spatial variability of weather data has mainly concentrated on long-term means such as annual or monthly averages. For example, for wind speed the correlation of monthly mean wind speed falls with increasing site separation. In the case of simple terrain (lowland England) the correlation is near 0.85 at distances below 30 km falling to around 0.75 beyond 100 km (Palutikof *et al.*, 1997). The correlations are lower in more complex terrain (Scotland). *Most studies of wind usually present maps for 'standard sites'. For example, Cook (1985) describes methods of converting observed winds to a common height of 10 m and to terrain which is flat and with a common roughness length, usually that which is typical of open country.*

In a study of low wind speed meteorology Smith (1992) compared wind direction for a network of six sites in northern and midland England. The root-mean-square (rms) wind direction differences derived from hourly data were compared for June and also for January–February in 1990 for sites whose separation varied from 55 to 370 km. The rms wind direction difference was below 20° for wind speeds above 19 kt for sites in lowland England up to 200 km apart, up to 40° when inland and coastal/upland sites were compared, and up to 80° when light wind (below 5 kt) occasions alone were considered.

Very few studies have compared the effect of spatially varying meteorology on dispersion estimates. In an internal Meteorological Office report Hollis (private communication) estimated Pasquill stability at a site using cloud data from a nearby site. Good results were achieved for two sites 45 km apart in a lowland area of eastern England.

Of greater importance for this study is the work of Davies and Thomson (1996) who compared dispersion estimates over a network of seven sites mainly in south-east England. Most of the sites were between 20 and 190 km of each other, although one site (Manchester) was further away from the main group, and the concentrations were found for a typical power station stack and a shorter factory source as means over a ten-year period. The main conclusions are that using weather data from sites of similar terrain up to 70 km away from a specific source was found to be sufficient for calculating the long-term mean and 98th percentile concentrations accurate to 7% and 10%, respectively, for a factory source. For the power station source it was found that only the site 20 km distant gave predictions of the long-term mean and 98th percentile concentrations accurate to 6% and 13%, respectively.

This report compares the dispersion estimates which have been calculated using weather data reported from a network of sites in central and southern England. The comparisons are made for all hours (annual) and for day and night in winter and summer. For simplicity, a flat site with

two stacks (one tall, one short), but no other buildings has been assumed so that it is only the differences in weather between the sites that affect dispersion.

## **2 Weather data**

The five-year period from January 1987 to December 1991 was chosen for the comparison. This was a period of relative stability in the observation network and 17 sites were chosen which had continuous records of hourly data. Figure 1 shows the sites which form a network covering central and southern England. One site was in South Wales (Rhoose). The site at Portland Bill was used because of its coastal location, but the reporting practices changed in the period so that only the daytime results could be used.

### **2.1 Comparison of the period 1987–91 with the 1961–90 average**

In Figures 2–7 some comparisons for wind speed and hours of sunshine are shown for monthly periods at Elmdon, Wattisham and Hurn. For sunshine the summer of 1987 was rather dull, but summer in 1989, and to some extent 1990, was sunnier than normal. Wind speeds were below average in 1987 and in many summer months throughout the period. The winter of 1990 was especially windy. Overall the above average spells were largely cancelled by periods of below average so that the five-year period did not depart very much from the long-period average for both sunshine and wind. However, the incidence of light wind/sunny conditions in summer do appear to be above normal.

## **3 Calculation of concentrations**

The ADMS model (version 2.11) (CERC Ltd) was used in statistical mode to calculate the surface concentrations. The modelling procedure incorporates a weather data pre-processor which allocates the raw data to one of twelve 30° wind direction sectors, to five wind speed classes, seven heat flux classes (based on total cloud cover, time of day and day of year), to seven boundary-layer depth classes and to three precipitation classes so that the original observations (43,800 in this case) are reduced to a much smaller number (around 2000). The calculations were done for a tall stack which emitted a buoyant plume (a typical power station source) and for a short stack which emitted gas only a little above ambient temperature to represent a small factory source.

When the ADMS model is run for a single hour of weather data an output file is produced which gives the ground-level concentrations. An area and grid length have to be specified which are appropriate to the scale of the dispersion. For the power station source the maximum concentration is usually within a few kilometres of the stack and the calculations were done for an area around the stack whose minimum distance was 10 km from the stack. This area where concentrations are calculated is called the domain. ADMS allows a limited number of grid points for the concentration calculations, so the grid length is chosen just to fit the domain. In the case of the short stack the peak concentrations are found nearer to the stack and the domain and grid length are smaller. The details of the stacks and the emissions are in Table 1.

The output concentrations are calculated at each grid point and for each hour. Therefore when all the weather data have been used there are about 2000 values of concentration at each of the grid points. The mean of these values gives the mean concentration at each grid point. Similarly, the 99th percentile value is found at each grid point. The maps (see Section 4) show these values. However, a comparison between the sites in Sections 5 and 6 is achieved by using the maximum value of the mean and 99th percentile concentration within the domain area.

**TABLE 1 Emission details**

Stack	Height (m)	Width (m)	Exit velocity (m s <sup>-1</sup> )	Temperature (C)	Domain (km × km)	Grid length (m)
Tall	130	7	15	150	20 × 20	640
Short	10	1	1	40	1 × 1	30

Both of the stacks were assumed to emit SO<sub>2</sub> at a rate of 1 kg s<sup>-1</sup> and the roughness length of the surrounding area was taken to be 0.1 m. It is important to note that no modification to the weather data was done even though ADMS allows the roughness lengths of the site of the weather data and the site of dispersion to be used. This corresponds to the simplest form of weather data interpolation, ie a straight substitution of one site to represent another. The calculations were done assuming flat topography with no building effects.

The concentrations were found for five cases:

- (a) all hours – a concentration over a five-year period referred to as an *annual concentration*,
- (b) daytime (0400–2000 hours) in summer – *summer day*,
- (c) daytime (0900–1500 hours) in winter – *winter day*,
- (d) night-time (2100–0300 hours) in summer – *summer night*,
- (e) night-time (1600–0800) in winter – *winter night*.

In each case maps of the mean and 99th percentile concentrations were produced and the spatial maximum value of the mean and 99th percentile concentration in the domain and their positions were noted.

#### **4 Maps of mean and 99th percentile concentration**

Figure 8 shows plots of mean and 99th percentile concentration in the domains of the tall and short stacks. The units of concentration are kg m<sup>-3</sup> on all the maps. The stack is at the centre of the map at point (0,0). The maps for the different sites were remarkably similar and so the results for only one site (Shawbury) are shown. For the tall stack the pattern of mean concentration shows a well-defined maximum to the north east of the stack generally 2–3 km from the stack. This is true for the annual map and for winter and summer both by day and by night. The 99th percentile concentration maps are similar to those for the mean concentration. The main exception is the map for *summer nights* which shows that the spatial peak of the 99th percentile concentration was sometimes not reached within the domain. However, the concentrations in this situation were much smaller than the others; these results were processed in the same way as the others.

The short stack results also show that the peak of mean concentration was found to the north east of the site in all the periods. The pattern of 99th percentile concentration is more like a ‘bull’s eye’, but the highest value is still usually to the north east of the source.

#### **5 Spatial peak of the mean concentrations – variation between results using different meteorological sites**

Instead of a presentation of the absolute values of the concentrations, the values are shown normalised by those which were calculated at Shawbury. This was done because Shawbury had concentrations which were often near the middle of the range for the 17 sites so that the spread of the concentrations at the sites relative to Shawbury can be seen easily.

## 5.1 Annual

Figures 9 and 10 show the results for the tall and short stacks. If the concentration at Shawbury is regarded as 1.0 then for the tall stack the concentrations range from 1.27 at Bristol to 0.82 at Wyton. The range is less for the short stack and is from 1.13 at Boscombe Down to 0.94 at Bristol. It should be noted that there are no results for Portland Bill because of missing night-time data.

## 5.2 Summer day

Figures 11 and 12 show results for the tall and short stacks. The results for the tall stack show a wide range from 1.35 (Bristol) to 0.43 (Portland Bill). The short stack shows a smaller range from 1.04 (Boscombe Down) to 0.72 (Portland Bill); however, nearly all the sites lie within the range 1.03 to 0.97. If the results for Portland Bill are excluded, then the variability is similar to that for the annual means (which did not include this site) in the case of the tall stack and significantly reduced in the case of the short stack.

## 5.3 Summer night

The results are shown in Figures 13 and 14. The range for the tall stack is from 1.5 (Herstmonceux) to 0.79 (Rhoose, Wyton and Boscombe Down) and for the short stack we have 1.73 (Boscombe Down) to 0.67 (Bristol). This is substantially more variable than the daytime, but the concentrations are less, especially for the tall stack.

## 5.4 Winter day

The results are shown in Figures 15 and 16. In this case the range for the tall stack is from 1.18 (Bristol) to 0.71 (Portland Bill) and for the short stack it is from 1.14 (Portland Bill) to 0.93 (Bristol).

## 5.5 Winter night

The results are shown in Figures 17 and 18. The tall stack shows a range from 1.06 (Herstmonceux) to 0.67 (Rhoose and Wyton) while for the short stack we have a range from 1.13 (Boscombe Down) to 0.85 (Bristol).

## 5.6 Summary

It is seen for the tall stack that Bristol and Herstmonceux are usually the two highest, while Boscombe Down, Rhoose, Wyton and Portland Bill are at the lower end. In the case of the short stack we tend to have the same sites appearing as extremes, but at the reverse positions. Hence Boscombe Down, Wyton, Rhoose or Gatwick appear with high values and Bristol and

**TABLE 2 Ratios of concentrations for the extreme sites**

Period	Tall stack	Short stack
Annual	1.55	1.20
Summer day	3.14	1.44
Summer day*	1.70	1.06
Summer night	1.90	2.58
Winter day	1.66	1.23
Winter day*	1.44	1.22
Winter night	1.58	1.33

\* Excluding Portland Bill.

Herstmonceux are at the low end. The short stack results from Portland are anomalous in the sense that for the summer daytime the concentrations at Portland are much lower than any other site. For the winter day Portland has the highest concentration of any site. Table 2 shows the ratios of the highest and lowest concentrations for the different periods and represents the extreme concentration ratios for the sites. A separate line shows results which exclude Portland: a considerable reduction in the ratios is achieved especially for the summer daytime.

## **6 Spatial peak of the 99th percentile concentrations**

Again the same procedure has been used as above so that the graphs show the concentration relative to that at Shawbury.

### **6.1 Annual**

The results are shown in Figures 19 and 20. The range for the tall stack is from 1.08 (Bristol) to 0.955 (Wyton and Rhoose) and for the short stack it is from 1.005 (several sites) to 0.975 (Bristol). The graph for the short stack shows a very uniform picture with most values very nearly the same.

### **6.2 Summer day**

The results are shown in Figures 21 and 22. The highest for the tall stack is Bristol at 1.09 and the lowest 0.75 at Portland Bill. Again the picture is more uniform for the short stack with most values between 1.05 and 0.97, except Portland Bill at 0.81.

### **6.3 Summer night**

The results are shown in Figures 23 and 24. The results for the tall stack show a very wide range from 1.33 (Bristol) to around 0.2 for eight sites. This is possibly because the domain did not capture the spatial maximum concentration for all the sites. Also the concentrations are very low for the tall stack at night so that this range of concentration ratios is not important. The domain for the short stack was large enough to capture the peak and the range is from 1.22 (Boscombe Down) to 0.85 (Bristol).

### **6.4 Winter day**

The results are shown in Figures 25 and 26. There is a range for the tall stack from 1.08 (Hurn and Herstmonceux) to 0.83 (Portland Bill), while the short stack has a range from 1.11 (Portland Bill) to just below 1.0 (11 sites).

### **6.5 Winter night**

The results are shown in Figures 27 and 28. Most of the concentrations are below that of Shawbury for the tall stack and the range is from 1.0 (Lyneham, Shawbury and Benson) to around 0.60 (Boscombe Down, Rhoose, Wyton, Wattisham and Gatwick). For the short stack we have a range from 1.09 (Rhoose, Wyton) to 0.98 (Bristol).

### **6.6 Summary**

In summary, the tall stack results tend to show the highest concentrations at Bristol, Herstmonceux and Lyneham and the lowest at Boscombe Down, Rhoose, Wyton and Portland Bill. This is very nearly the same order as for the mean concentrations. Again the short stack results tend to reverse the stations so that Bristol, Herstmonceux or Lyneham appear at the low end and

Boscombe Down, Rhoose and Wyton are nearer the top. This list of sites is also similar to the list for the mean concentrations. Again the behaviour at Portland Bill for the short stack is anomalous as it differs between winter and summer and gives extreme values. Table 3 shows the ratios for the extremes of the 99th percentiles; separate lines showing ratios with and without Portland Bill are given.

**TABLE 3 Ratios of 99th percentile concentrations for the extreme sites**

Period	Tall stack	Short stack
Annual	1.13	~1.0
Summer day	1.45	1.30
Summer day*	1.24	1.08
Summer night	6.65	1.44
Winter day	1.30	1.11
Winter day*	1.28	1.05
Winter night	1.67	1.11

\*Excluding Portland Bill.

## 7 Variation of concentration with distance

To show the effect of increasing distance from a site upon the representativity of the concentrations the ratios of the concentrations at the sites have been plotted against intersite distance. The distances between the sites vary from about 40 to 310 km. Some results are shown in Figures 29–35 for the tall and short stacks. There is no indication of a trend in either increasing or decreasing ratios with intersite distance and no indication of increasing scatter with distance. In fact, the two sites which often showed extreme high and low ratios (Rhoose and Bristol) are only 52 km apart. The anomalous results for Portland Bill are clear in the daytime results, but especially for the short stack in Figure 34 where the concentration ratios are around 0.7 with all the other sites regardless of distance from Portland.

## 8 Relation between concentration and the climate

It would be very useful to relate the concentrations to simple representations of the climate at the sites. In this way it would then be possible to use simple single-parameter climate data to infer regions which would be expected to have similar concentrations. Apart from wind direction the concentration depends on the wind speed and a measure of stability which is represented here by cloud cover or sunshine hours. ADMS also uses boundary-layer depth to estimate concentration, but this is not a routinely measured climate parameter and it was hoped that wind speed or stability would also represent this variable.

### 8.1 Using ADMS to investigate the effect of wind speed and stability

Some indication as to how the concentration is affected by wind speed and stability was found by running ADMS in single-hour mode for a range of wind speeds and stabilities. For the tall stack with neutral conditions we find that the surface peak concentration increases from very small values with light winds to reach a maximum value for winds of about  $13 \text{ m s}^{-1}$ . For very unstable conditions in mid-summer the concentrations are high at all wind speeds, but gradually decrease for wind speeds above  $4\text{--}5 \text{ m s}^{-1}$ . With moderate instability the concentrations are high for the lightest winds, then they fall as the speed increases to about  $4 \text{ m s}^{-1}$  before rising again at stronger winds.

The plume hardly reaches the ground for stable conditions. This is clearly complex behaviour so that over a long period a mixing of responses to wind speed is to be expected.

A similar analysis for the short stack shows a general decrease of the surface peak concentration as the wind speed increases for unstable conditions. For neutral and stable conditions there is a peak at about 4–5 m s<sup>-1</sup> with lower values for speeds below and above. Again over a long period a mixture of responses to wind is likely.

## **8.2 Variation of concentration with wind speed – tall stack**

An attempt was made to see if the site-to-site variation of the peak mean concentration averaged over the whole period, or for the day and night in summer and winter, was related to the wind speed averaged over those periods. The results for the tall stack are shown in Figures 36–40. In general, the concentration becomes less as the wind speed increases. This is particularly so for the daytime results in summer and in winter which have  $R^2$  values of 0.51 and 0.46, respectively. However, these are the periods which include Portland Bill (the site with the highest wind speed) and it is clear from the figures that Portland Bill is separate from the main group of stations. This pattern is a well-known cause of high correlations. The relation is weakest at night, but this is not surprising because some stable occasions will also be included when the plume barely reaches the ground.

These correlations are for 16 or 17 pairs of values and we note that for these numbers a value of  $R^2 = 0.25$  is significant at the 0.05 level and  $R^2 = 0.39$  is significant at the 0.01 level. Hence nearly all of the correlations between concentration and wind speed for the tall stack are significant at the 0.05 level and the daytime results for summer and winter are significant at the 0.01 level.

## **8.3 Variation of concentration with wind speed – short stack**

The correlations for the short stack are, in general, lower than for the tall stack (see Figures 41–45). Nevertheless there is a weak tendency for the mean concentration to increase as the wind speed increases. The main exception is for the daytime in summer when Portland Bill is very different from the other sites. Only the winter day correlation achieves significance at the 0.01 level.

## **8.4 Variation of mean concentration with wind direction – tall stack**

A striking feature of all the maps of concentration in Figure 8 is the location of the peak value in the east-north-east sector in relation to the source. It is to be expected that the mean concentration in a particular sector will depend upon the number of occasions that the wind carried emissions into that sector. This has been tested by plotting the mean concentration against the percentage of the time that the wind came from the west-south-west sector. The tall stack results for the whole period (annual) and for daytime in winter and summer are shown in Figures 46–48. On the whole, the associations are weak.

## **8.5 Variation of mean concentration with wind direction – short stack**

A similar analysis was done for the short stack with results shown in Figures 49–51. The correlations are rather higher than for the tall stack for the annual and winter day results, but in this case the concentrations decrease as the percentage of time in the sector increases. This is an unexpected result. It might suggest that a greater predominance of west-south-west winds is correlated with changes in other variables.

The methods in Sections 8.2–8.5 were also tried for the 99th percentile concentration. There is a high correlation between the mean and 99th percentile concentration so that similar relations between the 99th percentile concentration, wind speed and percentage in the west-south-west sector were found as for the mean concentration (relations not shown).

Attempts were also made to relate the mean concentration at the sites to mean cloud cover and sunshine hours. None of these attempts showed correlations as high as those for wind speed and direction. Other attempts which involved the use of a combined frequency such as the percentage of observations which were classed as 'windy and cloudy' or 'clear with light winds' also failed to improve upon the relations with wind alone.

Finally, some multiple linear correlations between concentration and wind speed and direction were derived, of the form:

$$C = a + b(\% \text{ wsw}) + c(U_{\text{mean}}) \quad (1)$$

where  $C$  = mean peak concentration for a period ( $\text{kg m}^{-3}$ ) for the emission details in Table 1, % wsw = percentage of time that the wind was in the west-south-west sector (ie 230–250°) for the period, and  $U_{\text{mean}}$  = mean wind speed for the period.

A period is the whole time from 1987–91 (annual), or the daytime or night-time in summer or winter.

The regression coefficients  $a$ ,  $b$ , and  $c$  are given in Table 4. In the table the regressions using wind speed and direction can explain just over half the variance in  $C$ . The summer night data are omitted as too unreliable.

**TABLE 4 Regression coefficients in equation 1 for tall stack**

Period	$A$	$b$	$c$	$R^2$
Annual	$4.34 \cdot 10^{-9}$	$7.44 \cdot 10^{-11}$	$-1.99 \cdot 10^{-10}$	0.56
Summer day	$1.39 \cdot 10^{-8}$	$1.04 \cdot 10^{-10}$	$-9.95 \cdot 10^{-10}$	0.59
Winter day	$3.79 \cdot 10^{-9}$	$4.24 \cdot 10^{-11}$	$-1.23 \cdot 10^{-10}$	0.56
Winter night	$1.19 \cdot 10^{-9}$	$1.18 \cdot 10^{-11}$	$-5.59 \cdot 10^{-11}$	0.37

## 9 Finding representative sites for dispersion calculations

The relations between concentration and wind speed that are discussed in Section 8 above can be used to find which stations should be used for dispersion calculations. So far the ratios of concentrations relative to Shawbury have been used to show the relations between concentration and wind speed. Figure 52 shows the ratio of annual mean concentration for the tall stack for all site pairs plotted against the ratio of the mean annual wind speeds at the sites. This gives 120 pairs of values. There is a scatter of points but also a negative correlation. Suppose that concentration ratios between 1.1 and 0.9 are acceptable, ie we are prepared to say that due to the limitations of the modelling procedure, the weather data, etc, an estimate of the concentration at some place between 1.1 and 0.9 of the mean annual concentration estimated at another site is adequate for our purpose. The next step is to choose wind speed ratios such that an acceptably small number of points lie outside the 1.1 and 0.9 concentration ratio limits. For example, if we choose 0.9 and 1.1 as the wind speed ratio limits then within those limits about 30% of the concentration ratios lie outside the concentration ratio limits of 0.9 and 1.1.

The procedure then to find suitable sites to represent the mean annual concentration at a site is as follows.

- (a) Estimate the mean annual wind speed for the site of the dispersion estimate. The Meteorological Office has prepared a mean annual wind speed dataset at 5 km resolution for the period 1961–1990. This was derived by using a regression procedure to relate station wind data to altitude, local topography, distance to coast etc and by fitting a surface to the resultant wind speeds. However, the fitted surface fits the station wind speeds exactly. Alternatively, data from a nearby weather station can be used with a procedure such as the WASP model which can make allowances for topography and surface roughness to estimate mean annual wind speed.
- (b) Find the ratio of the mean annual wind speed for the dispersion site and the mean annual wind speed for nearby sites with weather data.
- (c) Choose a weather station with a mean annual wind speed ratio between 0.9 and 1.1. Use the weather data from that site to estimate the dispersion.

By doing this we know that the dispersion estimate has about a 70% chance of lying between 1.1 and 0.9 of the true concentration, at least for the stack and emissions used in this report. As an example of the method, Figure 53 shows a map of England and Wales with contours of the annual mean speed ratio calculated against a point in Cambridgeshire which has a mean annual wind speed of 10 kt. It is clear that coastal areas have higher speeds with ratio values from 1.2 to 1.6. The mountainous areas of Wales and northern England also have large ratios. There are also large areas where the ratio is below 0.9, notably areas in south-east England, around Oxford and in the north Midlands. In this case the best station to use to represent dispersion in Cambridgeshire are the nearby stations with speed ratios close to 1.0, and we would choose Wittering, Marham or Wattisham probably. Benson and Brize Norton should be avoided. It would also be sensible to make a check using the station values of annual mean wind speed as well because the map is based on a fitted surface.

## 10 Discussion, conclusions and recommendation

The results show that the concentrations which are estimated for the tall stack are more sensitive to site than those for the short stack. On the whole, the 99th percentile concentrations are less sensitive to site than the mean concentrations. This would imply that the conditions which cause high concentrations are present rather uniformly over the area considered. The mean concentrations are most variable from site to site during the daytime in summer when the combinations of light winds and strong sunshine can lead to high surface concentrations. By contrast, if the interest lay with the annual 99th percentile concentration for the short stack then almost any site will do.

The results do not show a systematic change of concentration estimate with distance. This is at variance with Davies and Thomson (1996) who suggested that weather data from sites within 70 km for a factory source and 20 km of a power station source would give satisfactory estimates. The larger set of sites used here suggests that it is not distance so much as wind climate that matters. However, a nearby weather station should still be chosen provided that it has a similar wind climate.

Davies and Thomson also reported that the power station source was more sensitive to weather data and that result is borne out here as well. However those authors said that the 98th percentile concentration was more sensitive to the choice of weather data than the mean. The results from this work suggest the opposite provided that the 99th percentile can be compared with the 98th.

Certain sites, notably Bristol and Portland Bill, usually gave very high or low concentrations in comparison to the others. Portland Bill is at the end of a peninsula and has much higher wind speeds than the other sites, but at first sight it is not clear why Bristol should be unusual. If Bristol were used to estimate dispersion in the Avon/Wiltshire area then the results would be different compared with using weather data from Lyneham or Boscombe Down, for example. The site at Bristol is well within the city area and the anemometer is on the top of a building 44 m above the ground, but surrounded by other buildings so that the 'effective' height (ie the height used to compare it with other sites) is only 13 m. This is clearly quite a different sort of site compared to nearby sites which are all on airfields with open exposure on all sides and higher mean wind speeds. The results using Bristol data can serve as a warning about the difficulty of using urban measurements.

The relationships between the spatial peaks of the mean and 99th percentile concentration and simple climate variables, such as mean hours of sunshine or wind speed, were not strong. This is due to the averaging over many types of conditions and the complex effects any one parameter can have on the dispersion. For example, the surface concentration decreases as the wind speed increases for a passive ground-level source. However, for buoyant elevated sources the effects are not straightforward. Of the weather variables which were tried wind speed proved the most useful and it is possible to see broad changes in concentration with changing wind speed. A method to specify the most representative weather stations is proposed. This consists of using the nearest site with similar topography which has a mean annual wind speed within 10% of the site. This ensures a satisfactory estimate of concentrations for the tall stack with the least risk of error. The short stack has less stringent requirements so that if concentrations for the tall stack are estimated satisfactorily then the estimate for the short stack will also be adequate.

## 11 References

- 1 Cook, N J (1985). *The Designer's Guide to Wind Loading of Building Structures*. Part 1: *Background, Damage Survey, Wind Data and Structural Classification*. Garston and London, Building Research Establishment and Butterworths, 371 pp.
- 2 Davies, B M, and Thomson, D J (1996). Investigating the importance of pre-processing in estimating dispersion climatology. IN *Proceedings of the Ostend Workshop on Harmonisation of Dispersion Models*.
- 3 Palutikof, J, Holt, T, and Skellern, A (1997). *Wind, Resource and Hazard*. Chapter 11 in *Climates of the British Isles, Present, Past and Future* (M Hulme and E Barrow, eds). London, Routledge, 454 pp.
- 4 Smith, F B (1992). Low wind-speed meteorology. *Met. Mag.*, **121**, 141-151.

## PART B

### Combination of On-site and Remote-site Data

#### 1 Introduction

In some cases it is required to estimate dispersion using a mix of data from the site at which the dispersion estimate is needed and from a remote weather station. For example, observations of air temperature and cloud cover may be available at a site for which a dispersion estimate is needed, but without data on wind speed and direction which then have to be obtained from the nearest, most representative anemometer. This section of the report attempts to demonstrate the likely errors in dispersion estimates which are due to only having a partial set of weather data. The size of the weather dataset was restricted to three months and this also gave the opportunity to study the effects of using substitute weather data on dispersion estimates over shorter timescales than for Part A.

#### 2 Methods

It became clear in Part A that dispersion appeared to be more sensitive to wind than the other factors such as temperature or cloud cover. In a slight departure from the project proposal it was decided to make use of three sites with one used as a base site at which dispersion is calculated using the full set of weather data, while the other two are used to donate their wind data to the base site in turn. The three sites used are Heathrow, Gatwick and Stansted all of which are airports in the London area. The combinations of weather data are as follows:

- (a) Heathrow data alone (temperature, cloud and wind): H,
- (b) Heathrow (temperature and cloud) + Gatwick (wind): HG,
- (c) Heathrow (temperature and cloud) + Stansted (wind): HS.

Dispersion calculations were done using ADMS for the tall and short stacks as in Part A for the period from June to August in 1992. Statistical runs were performed on four-days' worth of hourly data, ie 96 hours in each run, so that in total 23 sets of four-day runs were done to cover the three-month period. This allowed the variability in the dispersion error to be found over relatively short periods of four days. The results are presented using the spatial maximum of the average and 99th percentile concentration for each four-day run. In addition, a statistical run was done for the entire three-month period using sequential hourly data.

#### 3 Results

##### 3.1 Weather in summer 1992

A summary of the weather data during the summer of 1992 is shown in Table 5. This shows that winds were generally light in June and July, but August was breezy. Stansted always had higher winds than the other two sites, but Gatwick was similar to Heathrow in July and August although windier in June. These wind speed differences can be broadly related to the site characteristics and wind direction. In June winds were mainly north-easterly which, for Heathrow, is the most sheltered direction because the main terminal building complex begins at about 1 km from the anemometer in that direction. Similarly in July winds were from the south and south-west, which corresponds to a sheltered direction at Gatwick and we note from Table 5 that the July winds at Gatwick were not stronger than those for June, although they did increase at the other sites. The

sunshine totals were very close at all the sites. June had slightly more hours of sunshine than normal, but July and August were rather dull.

### 3.2 Comparison of concentrations for the entire three months

From the run of the entire three month period were extracted the spatial maximum of the average and of the 99th percentile concentrations and are compared in Table 6. The table shows that the use of Gatwick or Stansted winds with Heathrow temperature and cloud resulted in an overestimate of the concentrations at Heathrow. The exception is for the 99th percentile results for the short stack.

**TABLE 5 Monthly mean wind speed and sunshine hours at Heathrow, Stansted and Gatwick for June–August 1992. The 1961–90 average is in brackets**

Site	Wind speed (kt)		
	June	July	August
Heathrow	3.8 (7.6)	5.2 (7.4)	7.1 (7.2)
Stansted	6.6 (7.6)	7.4 (7.4)	10.0 (7.4)
Gatwick	5.6 (6.9)	5.6 (6.7)	6.7 (6.5)
	Sunshine (hours per day)		
Heathrow	7.12 (6.62)	5.12 (6.27)	4.81 (6.02)
Stansted*	7.15 (6.56)	4.78 (5.83)	5.24 (5.40)
Gatwick	7.56 (6.81)	5.55 (6.60)	5.09 (6.30)

\* Data for Rothamsted.

**TABLE 6 Values of H/HG and H/HS for the 3 months June–August 1992, derived from hourly sequential data, for the maximum value of average concentration and the maximum value of the 99th percentile concentration**

Ratio	Short stack		Tall stack	
	Average	99th percentile	Average	99th percentile
H/HG	0.76	1.23	0.84	0.87
H/HS	0.95	1.57	0.84	0.75

### 3.3 Comparison of concentrations for four-day periods

A comparison of the spatial maximum of the average and of the 99th percentile concentration for four-day periods is found by using the ratios of concentrations, ie H/HG and H/HS, which therefore compare the concentrations at Heathrow using all the weather data from Heathrow with the mixtures of weather from Heathrow and from the other two sites. The results for the tall stack are in Figures 54–57 and for the short stack in Figures 58–61.

In the case of the tall stack the ratios H/HG lie mainly between 0.5 and 1.5 (average maximum) and 0.7 and 2.0 (99th percentile) with a few four-day periods outside of this range. In the case of H/HS the range for the average maximum is typically between 0.5 and 1.5 and for the 99th percentile from 0.8 to 2.0. Some four-day periods had ratios much larger than this.

The results for the short stack show a slightly smaller range. The values of H/HG are mainly between 0.5 and 2.0 (average maximum) and 0.9 and 1.5 (99th percentile), while H/HS is from 0.8 to 2.0 (average maximum) and from 1.0 to 1.6 (99th percentile). There seems to be more of a bias in the short stack results so that using winds from either Stansted or Gatwick generally results in an underestimation of concentrations at Heathrow. On the whole, there is least variability

in the four-day ratios for the tall stack in August which was a windy and rather dull month. The variability of the short stack ratios is similar throughout.

An alternative way of looking at the data is to use the number of the four-day periods which would give an estimate of the mean and 99th percentile concentration at Heathrow in the range 0.9 to 1.1 which is presumably the range of what is acceptable. Table 7 gives the results.

**TABLE 7 Numbers of four-day periods (maximum 23) which have H/HG or H/HS in the range 0.9 to 1.1**

Ratio	Tall stack		Short stack	
	Mean	99th percentile	Mean	99th percentile
H/HG	4	8	8	8
H/HS	8	11	6	4

### 3.4 Hourly data for a four-day period

As an example of how the wind and concentration vary from hour to hour, the hourly data for 20–24 August 1992 are presented in Figures 62 and 63. In Figure 62 the peak hourly concentration for the short stack is shown. The concentration is highest by day and falls to very low values at night except for the first night when H and HS show values only a little below daytime values. The daytime concentrations are generally highest for H with HS lowest. A check on the winds in Figure 63 suggests that Heathrow has the lightest winds by day with the high concentrations at Heathrow coinciding with lighter winds at that site (eg hours 37–40). The spell of high night-time concentrations for H and HS, but not for HG, are seen to be in a period of stronger winds at Heathrow and Stansted, but not at Gatwick (hours 22–23). The ratio of H/HG is mainly between 0.9 and 1.4 during the day, but with occasional very large ratios. For example, for the hours 22 and 23 mentioned above the ratio was over 200,000, ie for these two hours using Gatwick winds to represent Heathrow would have caused a very large error in the concentration estimate.

## 4 Summary

The results show that using wind data from either Gatwick or Stansted with temperature and cloud from Heathrow does not give a good estimate of concentrations at Heathrow for a three-month summer period and also on many four-day occasions. If the range of H/HG or H/HS from 0.9 to 1.1 is used as the range of what is acceptable, then the ratio falls within this range for between one-fifth and one-quarter of the four-day periods in the summer months of 1992 and not more than half the time for any category (Table 7). On the whole, the estimates for the short stack are rather worse than for the tall stack due to more of a bias to the underestimation of concentration.

# Overall Recommendations

## Part A

For statistical runs over five to ten years choose weather stations which have nearly the same mean annual wind speed and which as far as possible are similar as regards topographical setting, altitude, nearness to coastline, etc. In particular, coastal sites should not be used to represent inland areas. For sites on the coast then use a weather station that is on a coast which faces the same direction. Wind data from urban sites should not be used to represent dispersion in rural areas without modification to allow for the different roughness.

## Part B

Good estimates of dispersion will only be obtained if the wind speed and direction can be estimated satisfactorily: choose wind data from the nearest site with a similar topographical setting and local roughness length, or make a correction for the different roughness lengths. It is unlikely that dispersion estimates for individual hours or for periods as long as four days will be satisfactory without on-site wind data.

## Recommendations for further work

Weather data are used in dispersion calculations in the following sequence.

- (a) Estimate the weather at the site of dispersion. This usually means 'surface' data.
- (b) Bin it for statistical calculations (optional).
- (c) From the surface weather data estimate the weather conditions at the height of the release.
- (d) Finally it is assumed that the years of weather data which are used are representative of the longer term.

In Section 3 of Part A was stated that the method of using weather data in this report was substitution, ie the weather data from a site are assumed to represent another place without modification. Ideally, dispersion estimates would be better if we could produce a stream of hourly weather data at any place which would match exactly what would be recorded there if instruments were put in place. Instead of substitution we could use physical models to modify the weather data so that they represent the site of dispersion better. An example is the use of roughness lengths to modify the wind speeds and models such as FLOWSTAR to allow for topography. We could also use statistical interpolation methods to estimate variables which are more continuous in nature such as wind direction, temperature or cloud cover. An example is inverse distance weighting, but such methods only work satisfactorily if there are at least three stations distributed evenly around the site of interpolation.

Item (c) in the above list mainly concerns the wind and turbulence profiles in the lower atmosphere. This topic is beyond the scope of the Atmospheric Dispersion Modelling Liaison Committee and we can only use the results of micrometeorological research studies.

Item (d) refers to climate variations on the scale of a decade or so. During the past 40 years (the period for which there is a computer archive of weather data) some slow changes have happened. In Part A it was mentioned that the five-year period of this study had an above-average number of light wind strong radiation hours in summer. Other periods with above/below-average wind speeds for example can also be found.

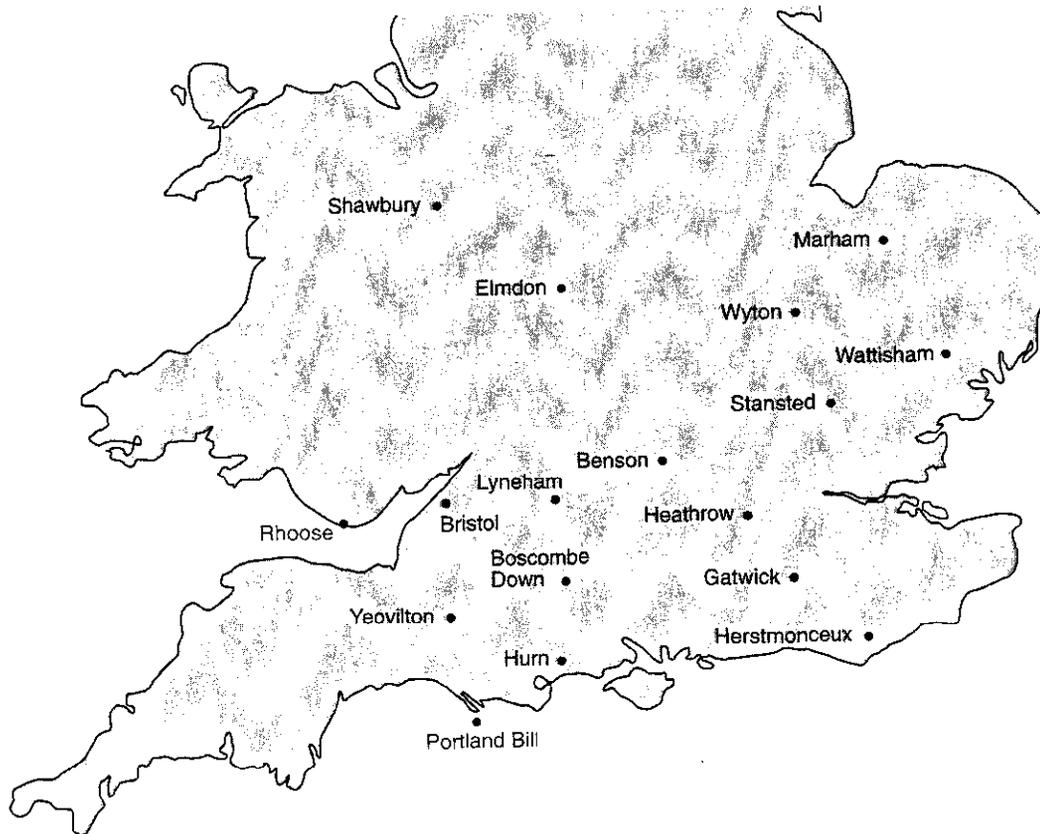
Further work can be recommended on:

- (a) use of physical methods to improve the estimation of winds, eg roughness lengths,
- (b) a comparison of dispersion estimates for the periods 1961–70, 1971–80 and 1981–90 for a few sites with complete records.

### **Acknowledgements**

We would like to thank Andrew Mirza for helping with the computing aspects of Part B and John Ashcroft who provided Figure 53 from the Meteorological Office geographical information system. David Thomson suggested several improvements to the final draft.





**FIGURE 1** Sites at which concentrations were estimated for the period 1987-91

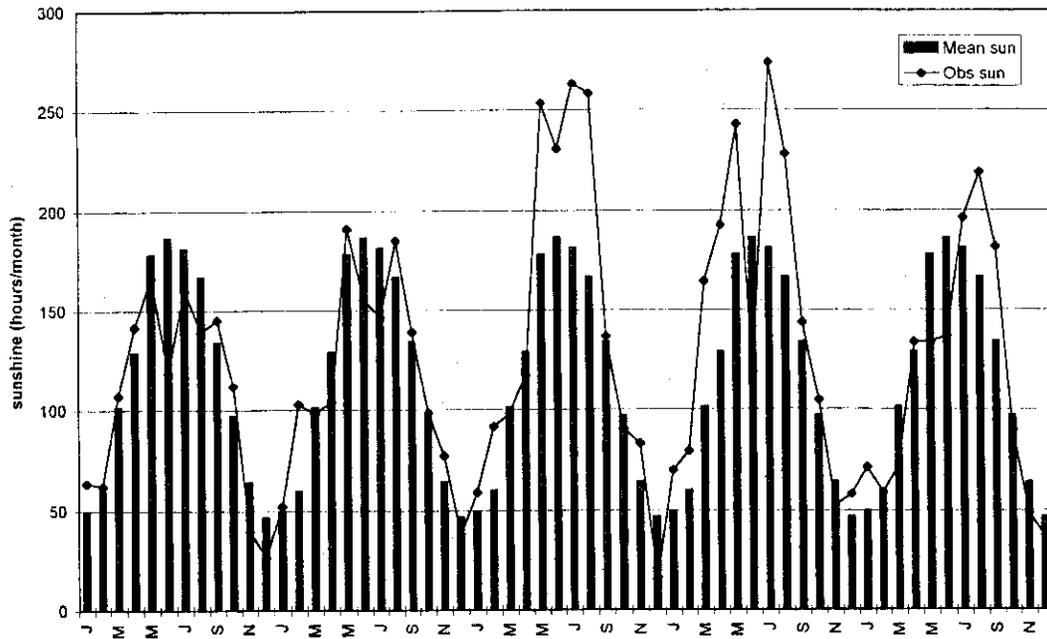


FIGURE 2 Elmdon: observed monthly hours of sunshine for 1987-91 compared with the average

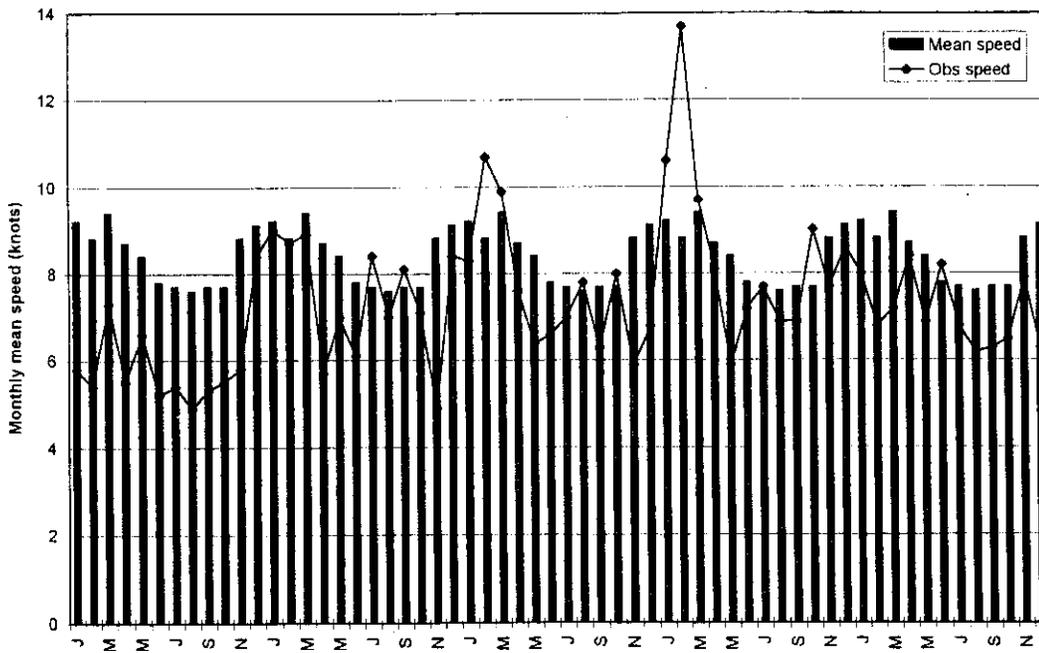
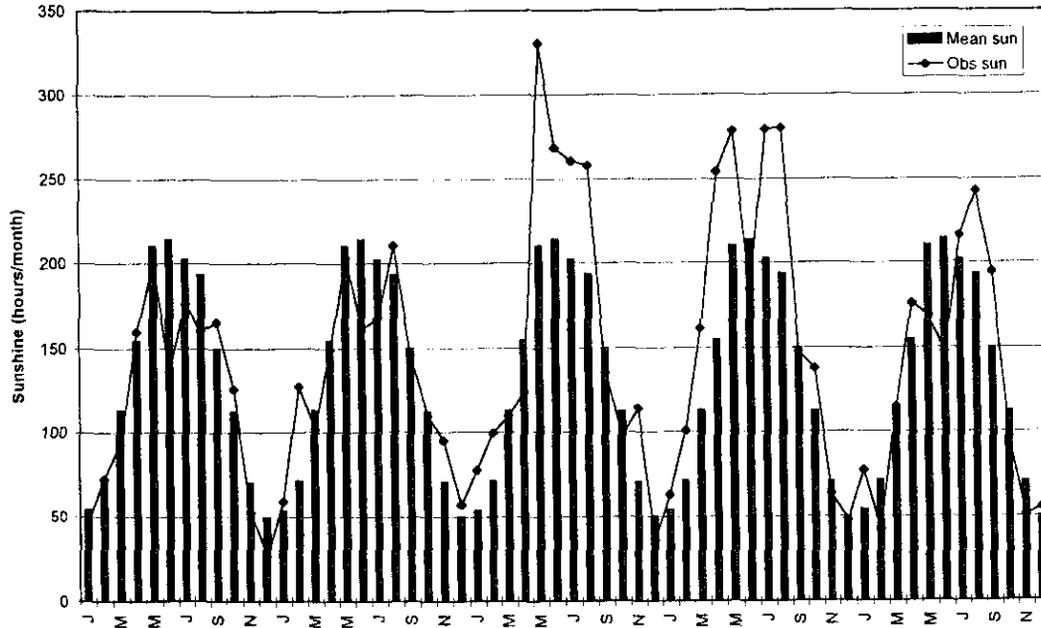
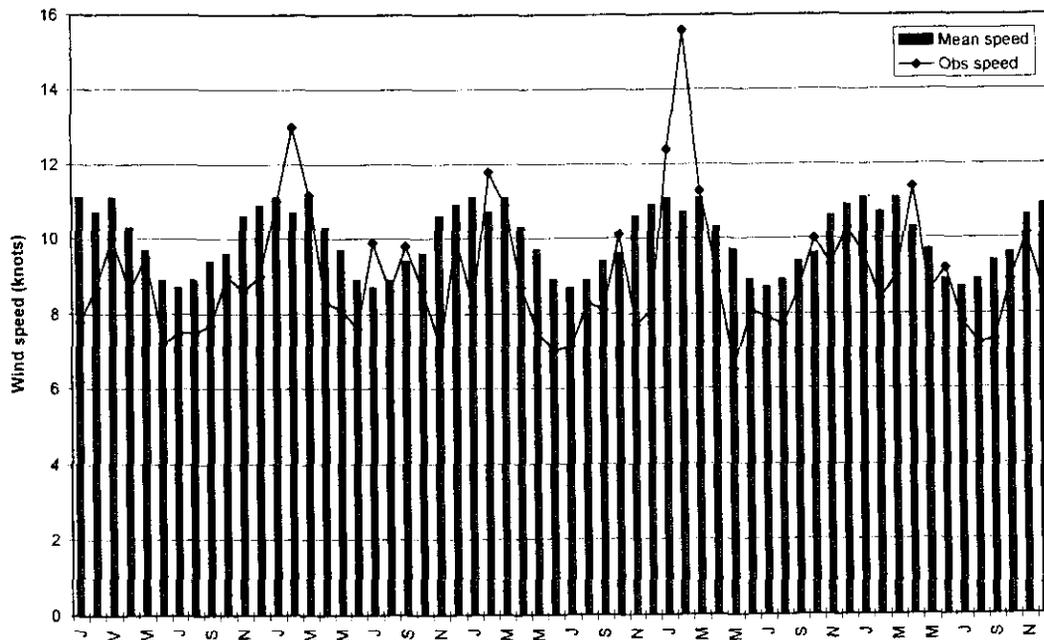


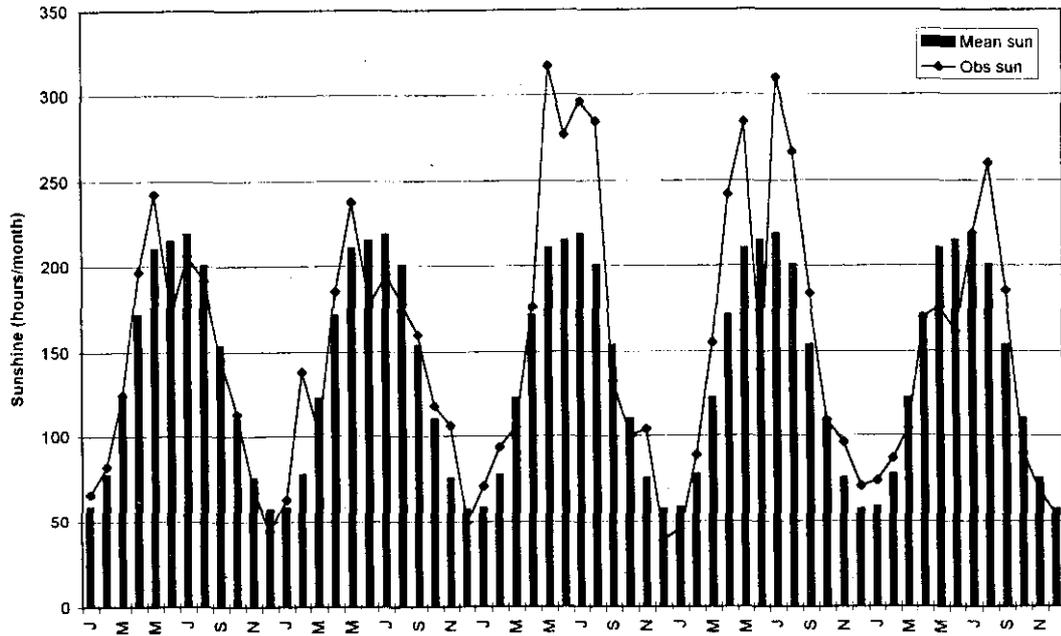
FIGURE 3 Elmdon: observed monthly mean wind speed for 1987-91 compared with the average



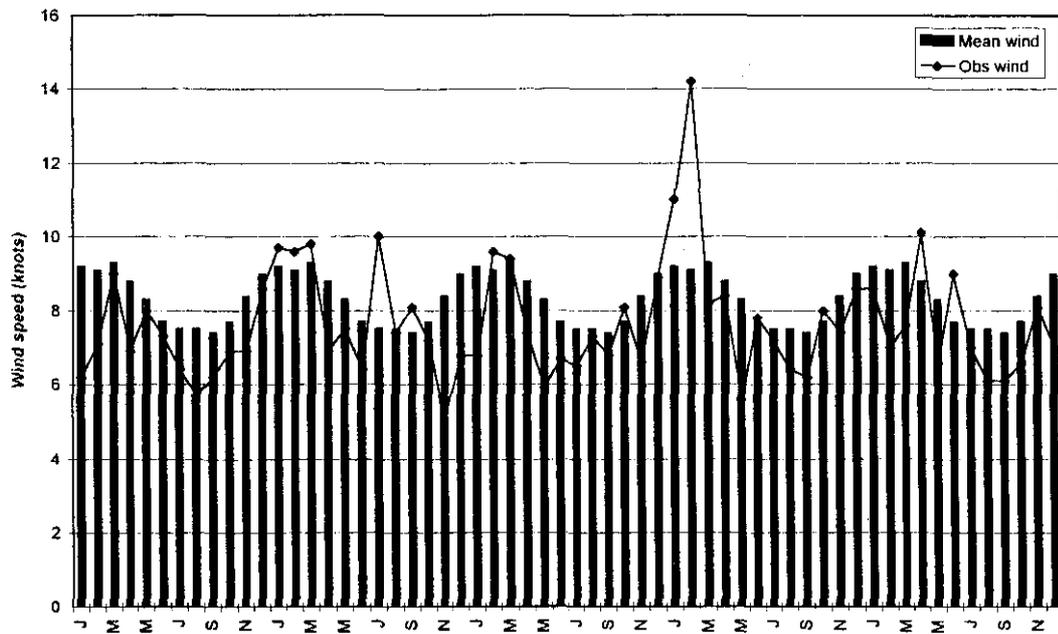
**FIGURE 4** Wattisham: observed monthly hours of sunshine for 1987-91 compared with the average



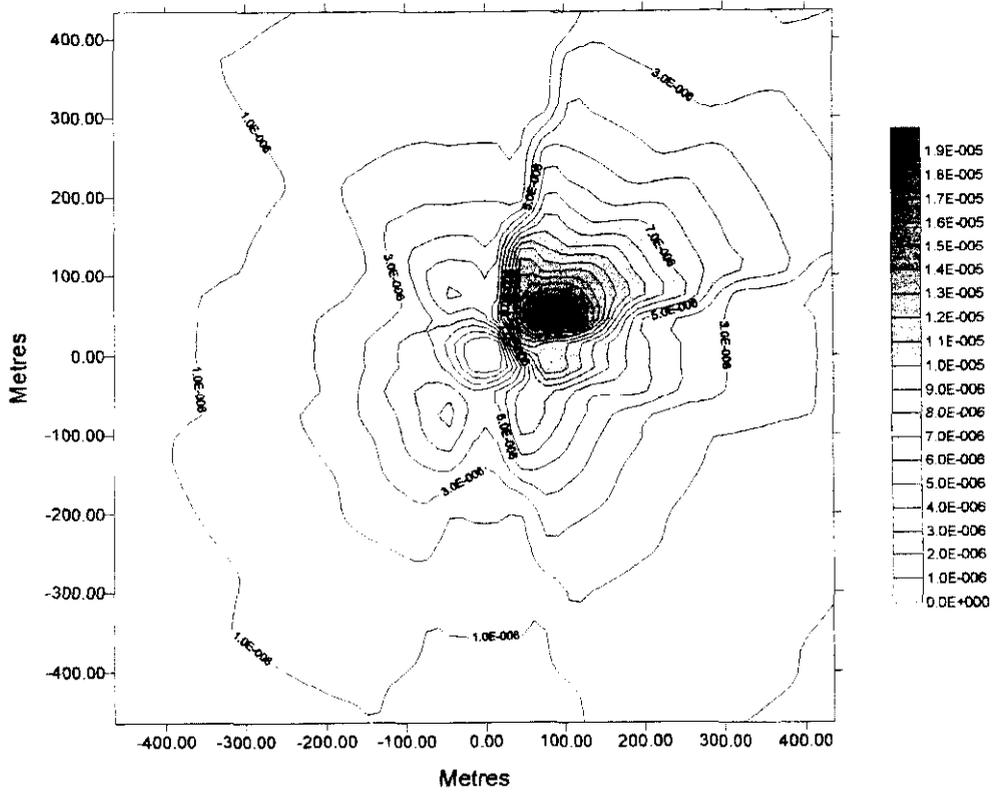
**FIGURE 5** Wattisham: observed monthly mean wind speed for 1987-91 compared with the average



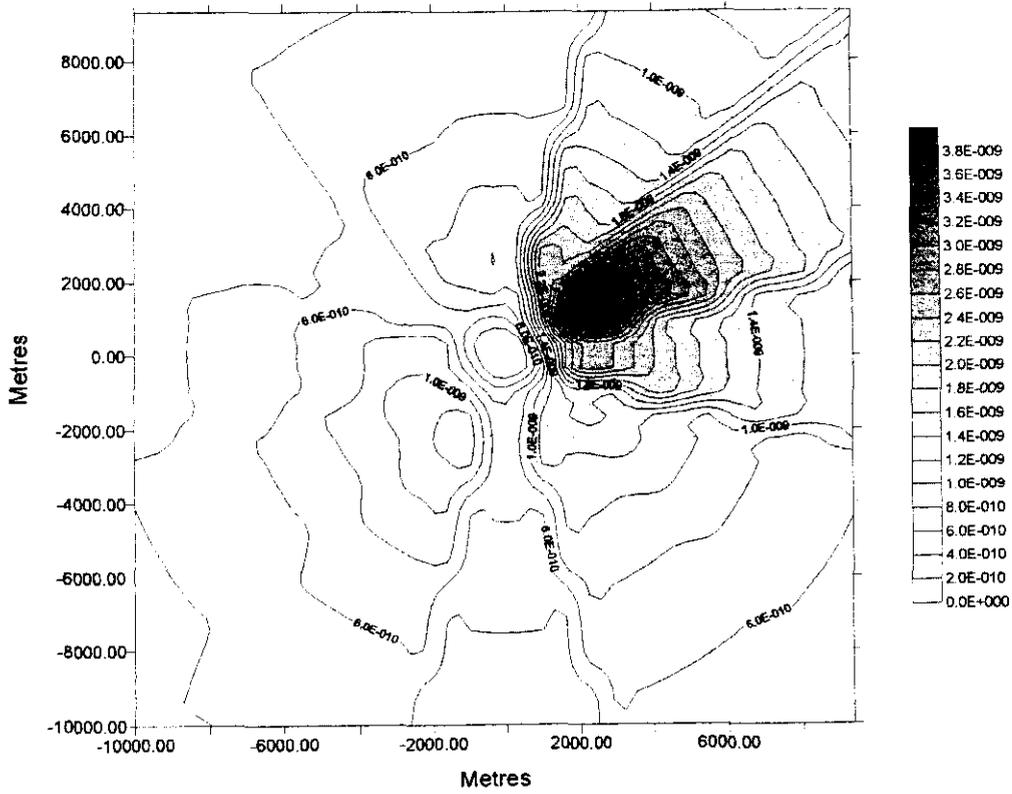
**FIGURE 6** Hurn: observed monthly hours of sunshine for 1987-91 compared with the average



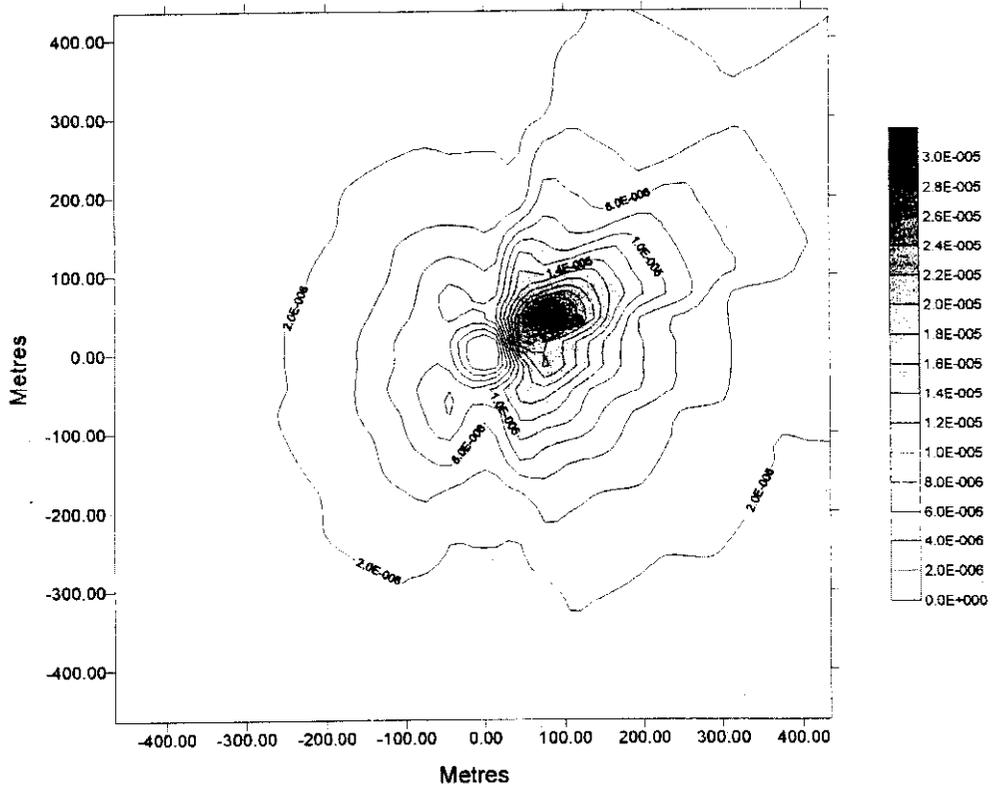
**FIGURE 7** Hurn: observed monthly mean wind speed for 1987-91 compared with the average



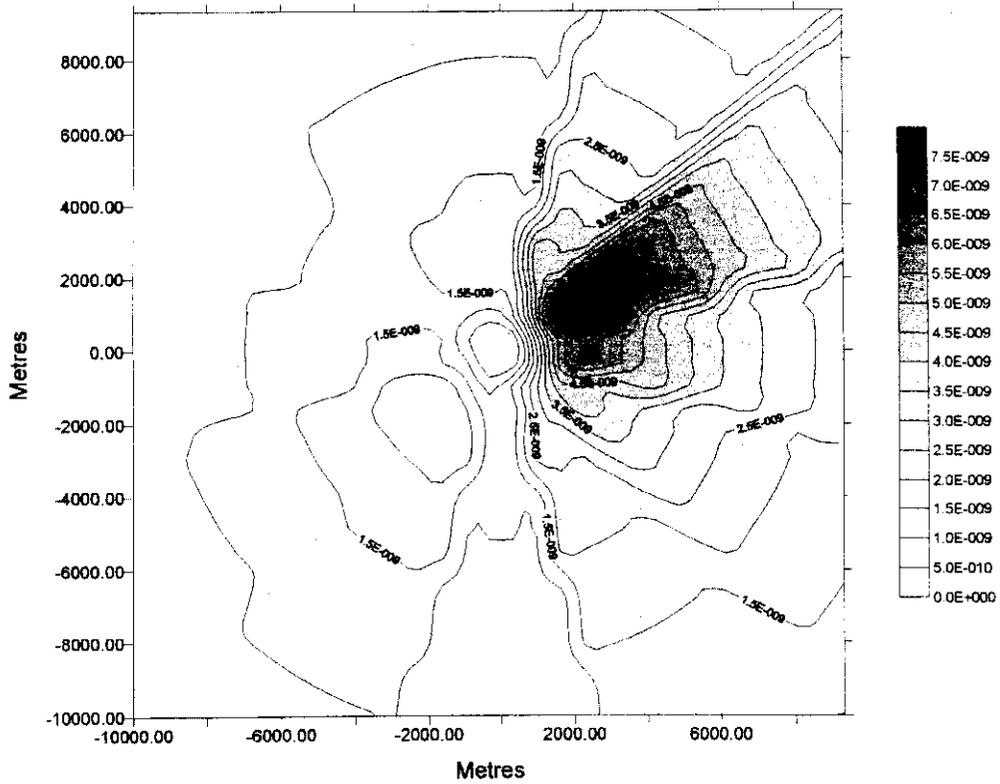
**FIGURE 8(a) Long-term mean of concentration for Shawbury, annual run, short stack, pollutant: SO<sub>2</sub>**



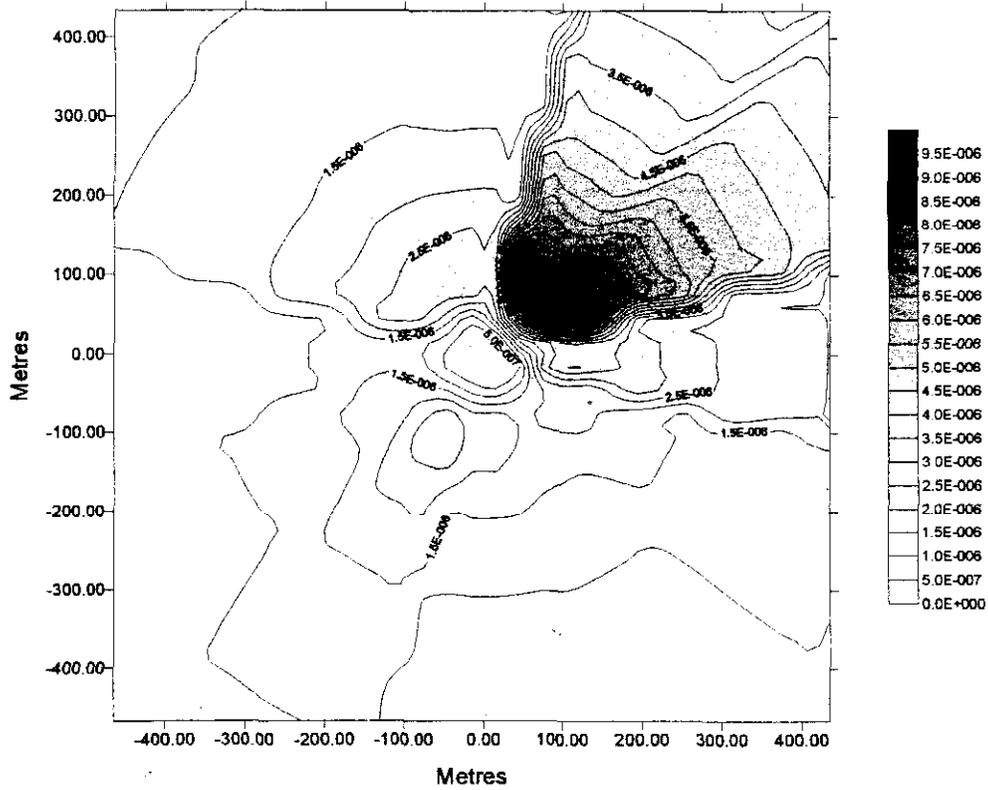
**FIGURE 8(b) Long-term mean of concentration for Shawbury, annual run, tall stack, pollutant: SO<sub>2</sub>**



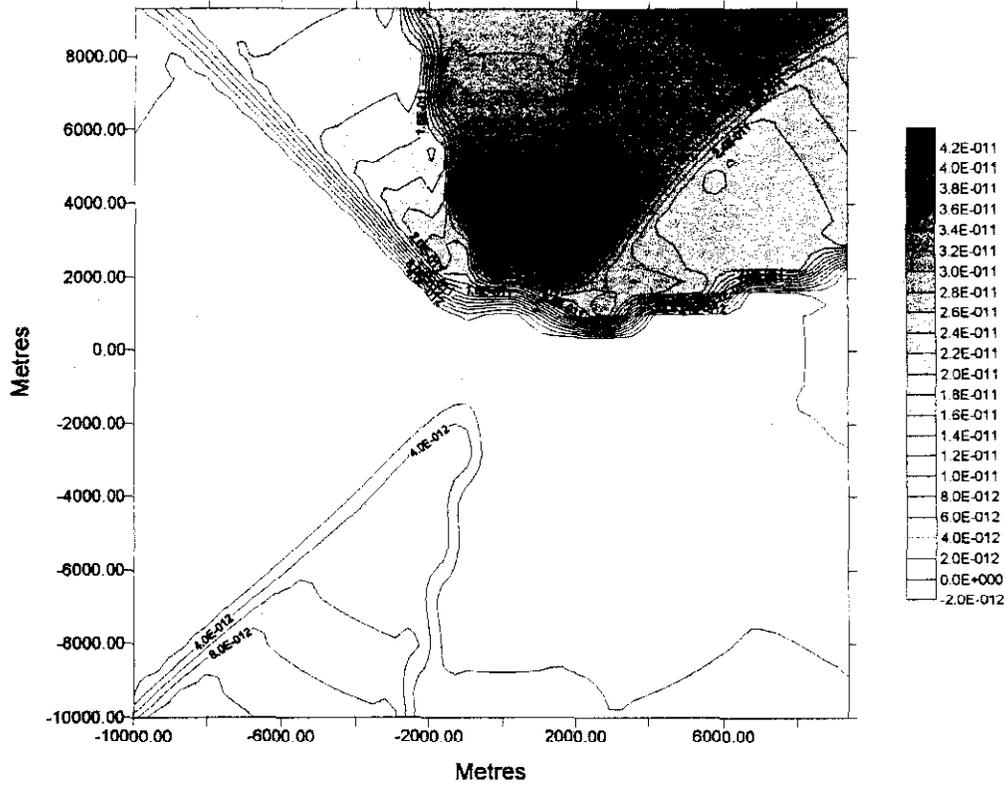
**FIGURE 8(c) Long-term mean of concentration for Shawbury, summer day run, short stack, pollutant: SO<sub>2</sub>**



**FIGURE 8(d) Long-term mean of concentration for Shawbury, summer day run, tail stack, pollutant: SO<sub>2</sub>**



**FIGURE 8(e) Long-term mean of concentration for Shawbury, summer night run, short stack, pollutant: SO<sub>2</sub>**



**FIGURE 8(f) Long-term mean of concentration for Shawbury, summer night run, tall stack, pollutant: SO<sub>2</sub>**

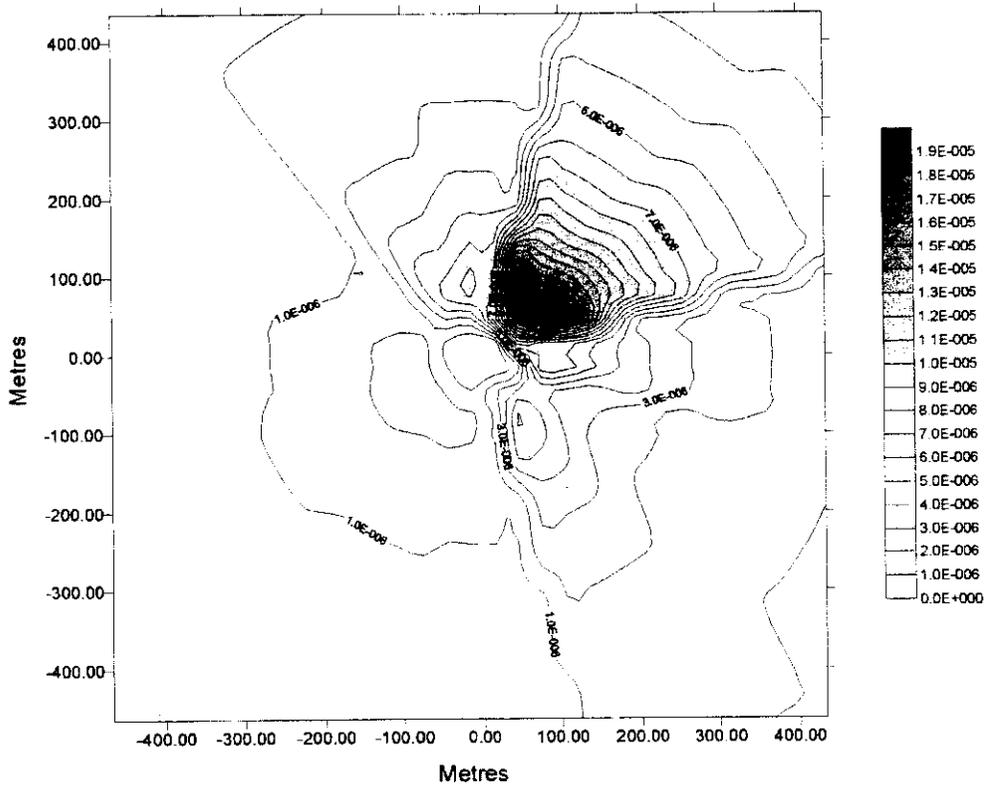


FIGURE 8(g) Long-term mean of concentration for Shawbury, winter day run, short stack, pollutant: SO<sub>2</sub>

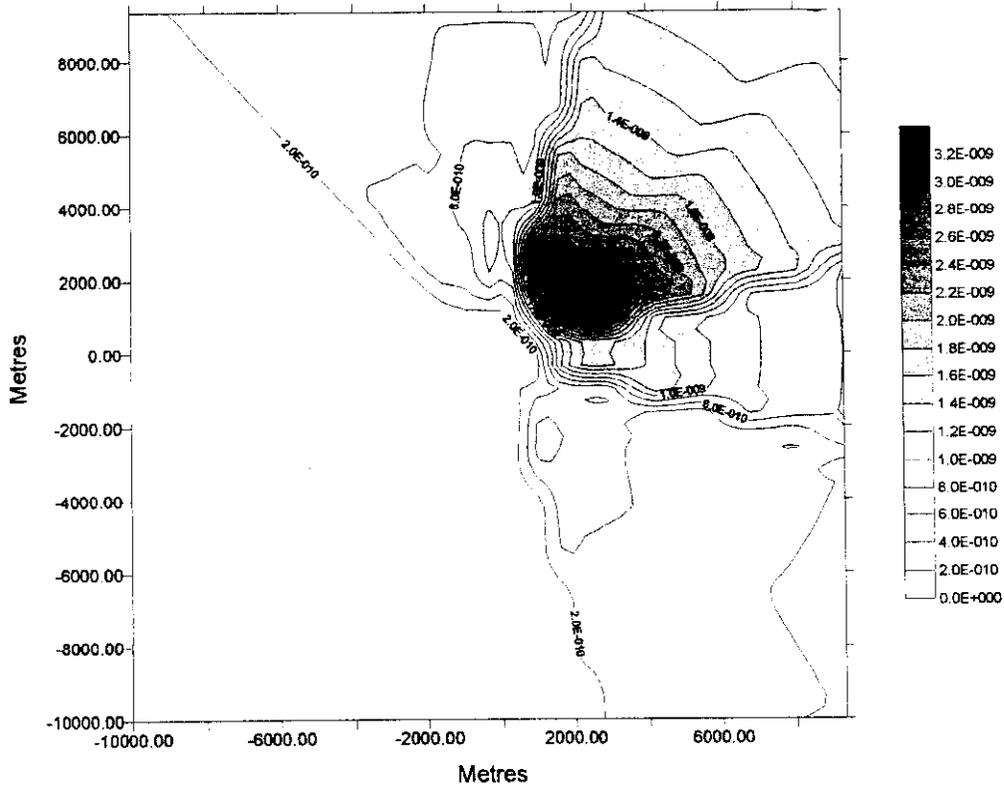


FIGURE 8(h) Long-term mean of concentration for Shawbury, winter day run, tall stack, pollutant: SO<sub>2</sub>

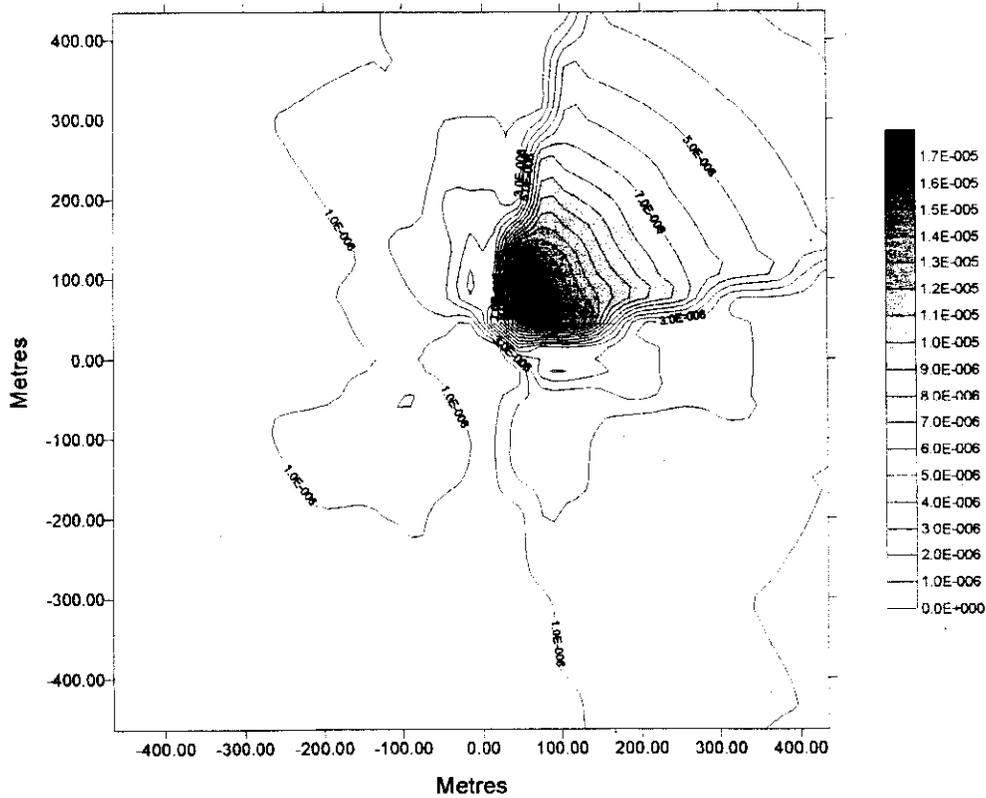


FIGURE 8(i) Long-term mean of concentration for Shawbury, winter night run, short stack, pollutant: SO<sub>2</sub>

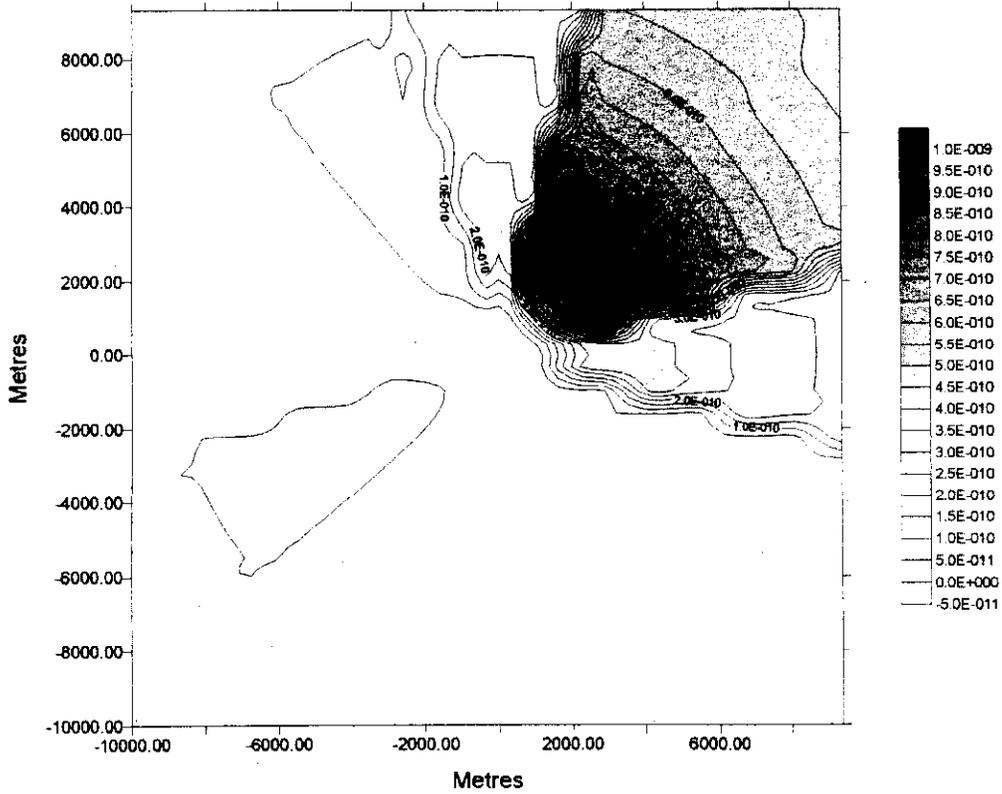


FIGURE 8(j) Long-term mean of concentration for Shawbury, winter run, tall stack, pollutant: SO<sub>2</sub>

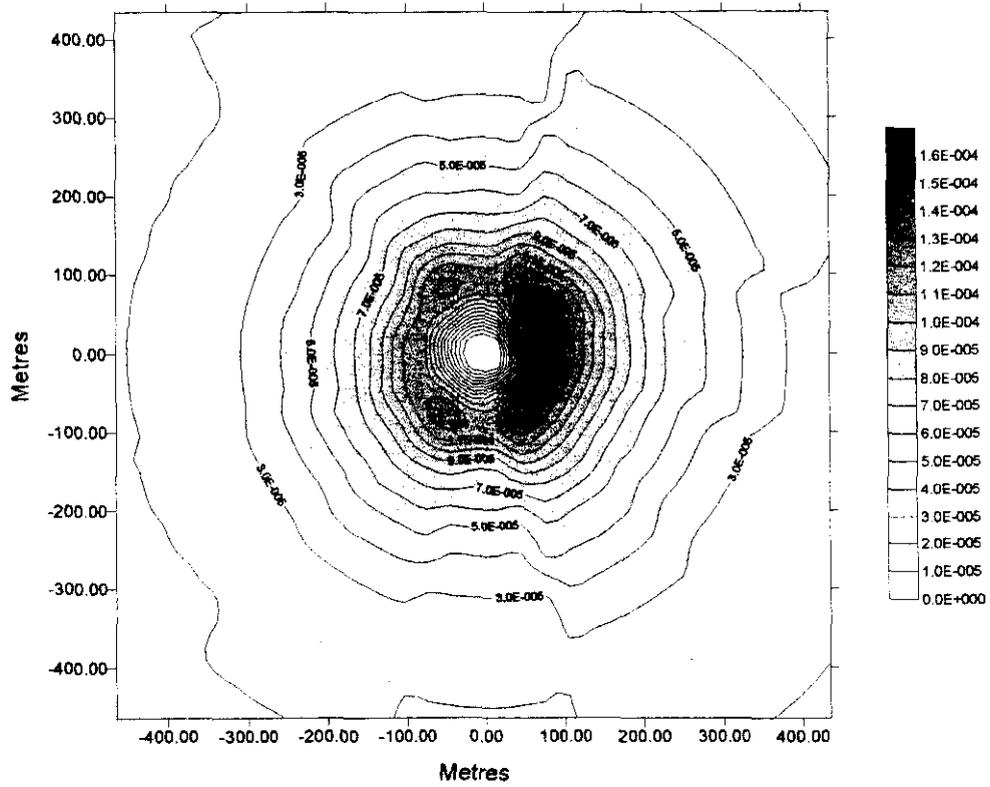


FIGURE 8(k) 99th percentiles of concentration for Shawbury, annual run, short stack, pollutant: SO<sub>2</sub>

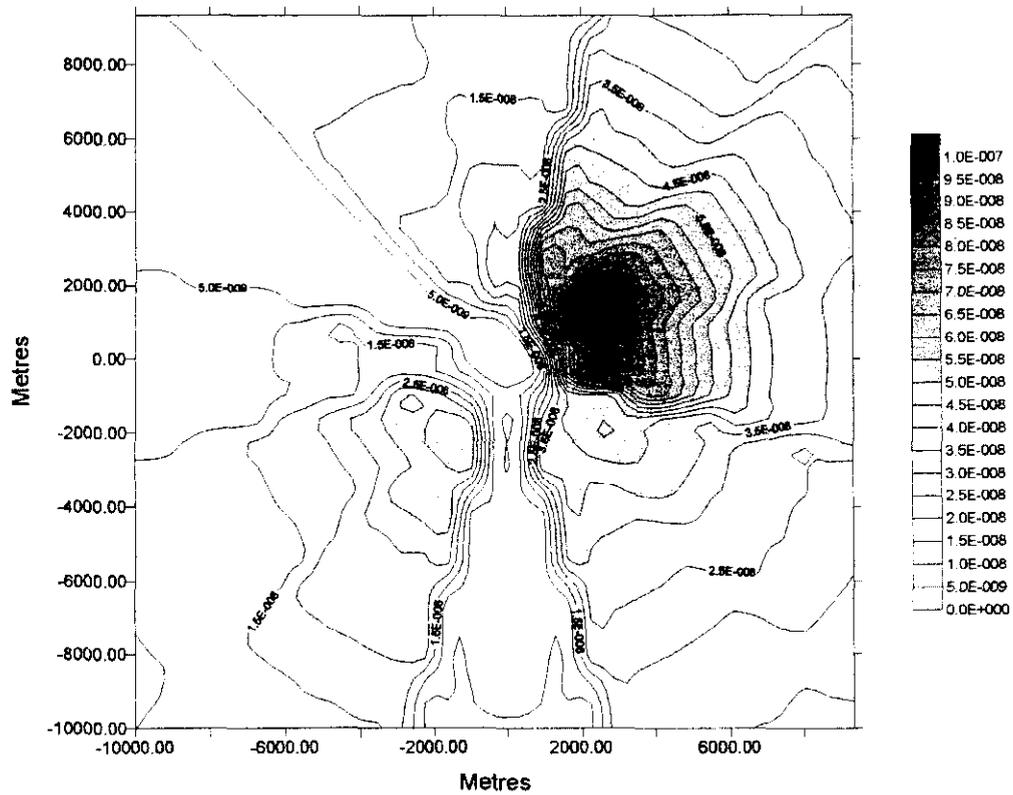


FIGURE 8(l) 99th percentiles of concentration for Shawbury, annual run, tall stack, pollutant: SO<sub>2</sub>

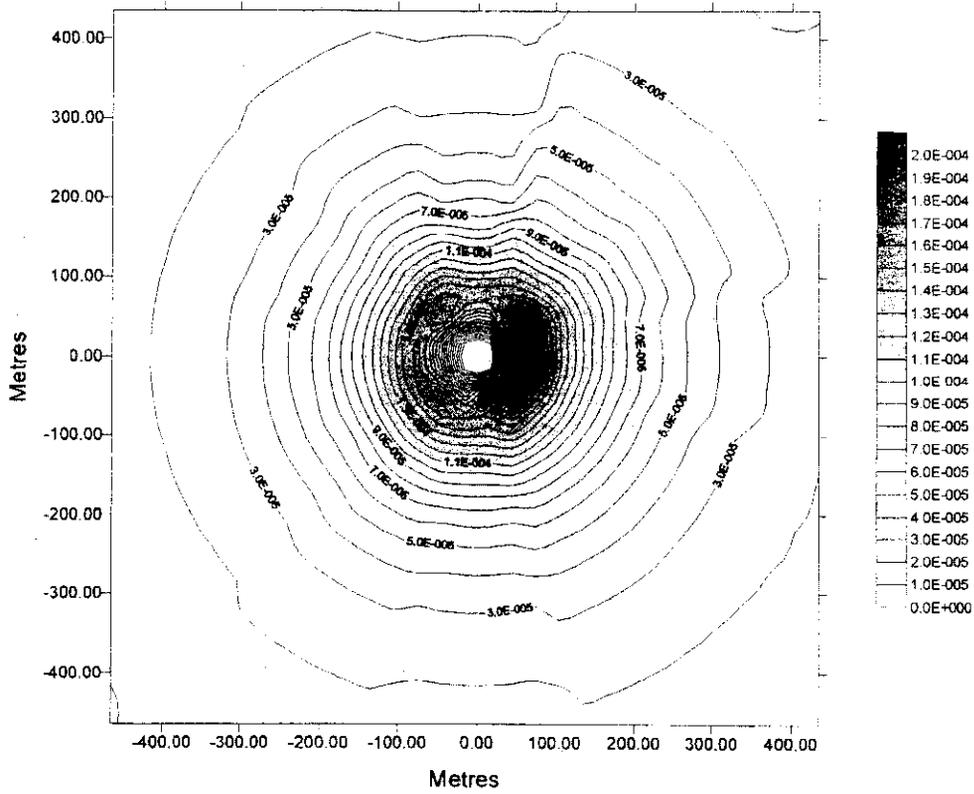


FIGURE 8(m) 99th percentiles of concentration for Shawbury, summer day run, short stack, pollutant: SO<sub>2</sub>

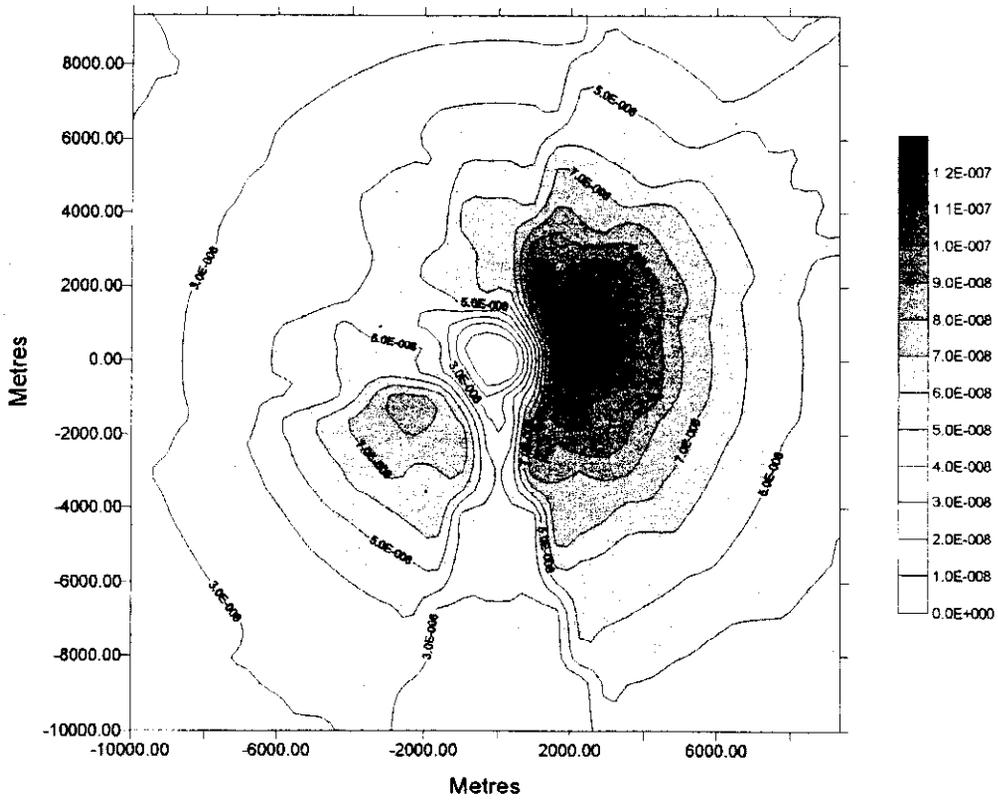


FIGURE 8(n) 99th percentiles of concentration for Shawbury, summer day run, tall stack, pollutant: SO<sub>2</sub>

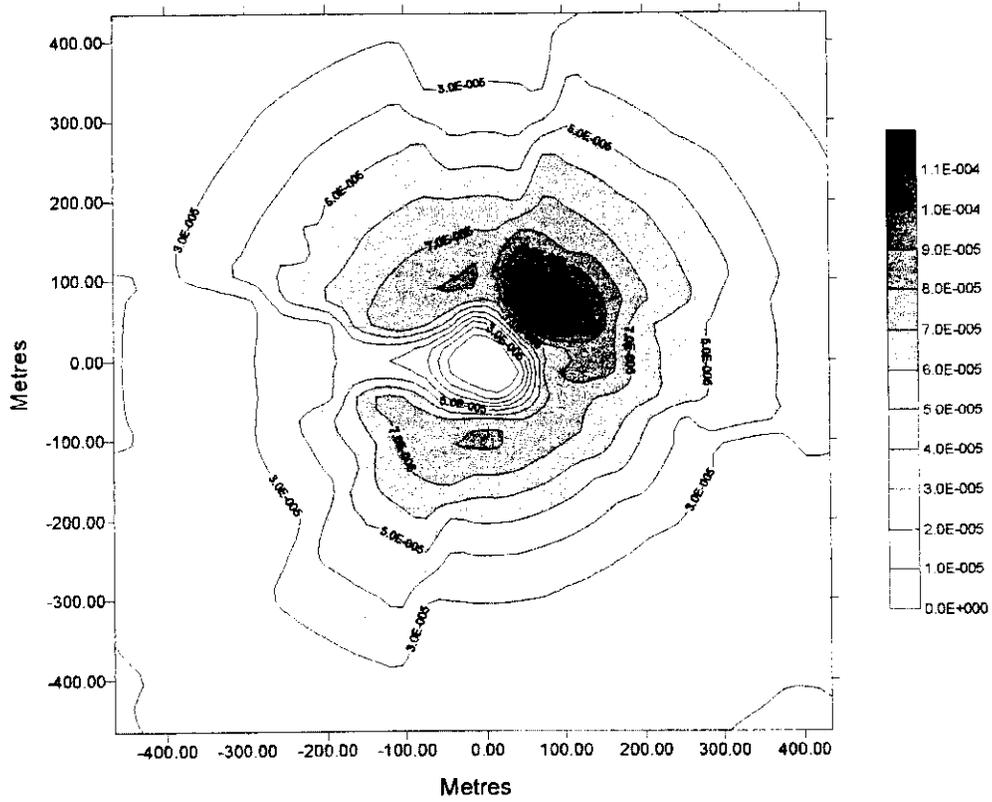


FIGURE 8(o) 99th percentiles of concentration for Shawbury, summer night run, short stack, pollutant: SO<sub>2</sub>

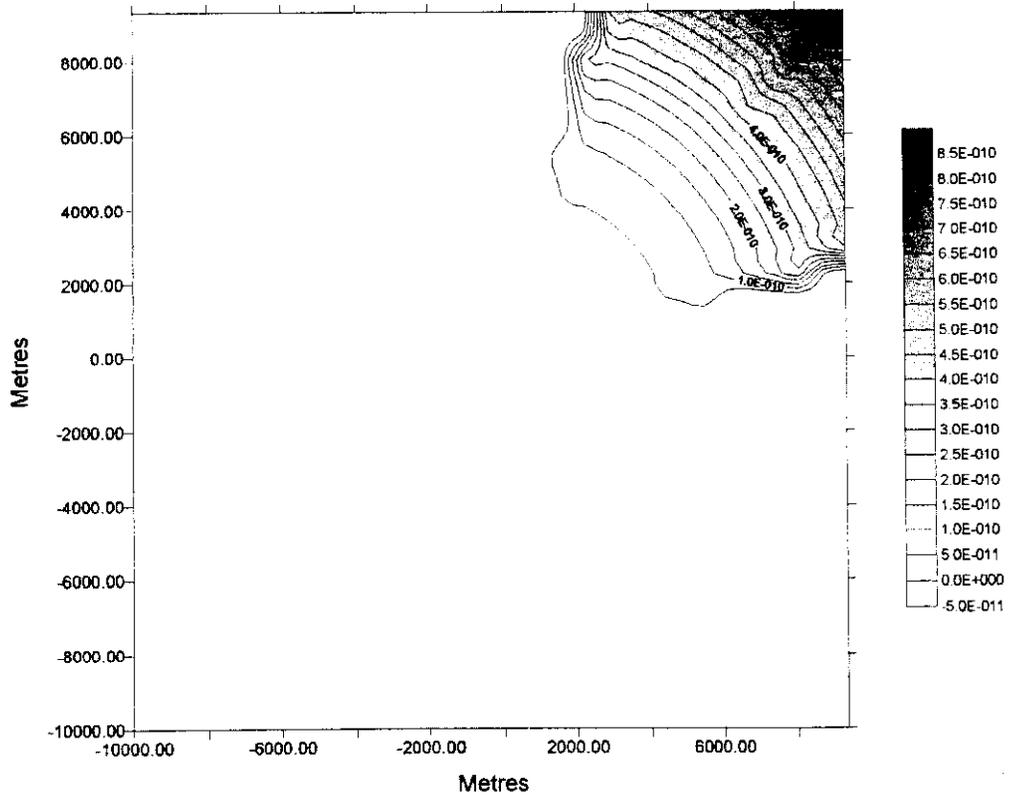


FIGURE 8(p) 99th percentiles of concentration for Shawbury, summer night run, tall stack, pollutant: SO<sub>2</sub>

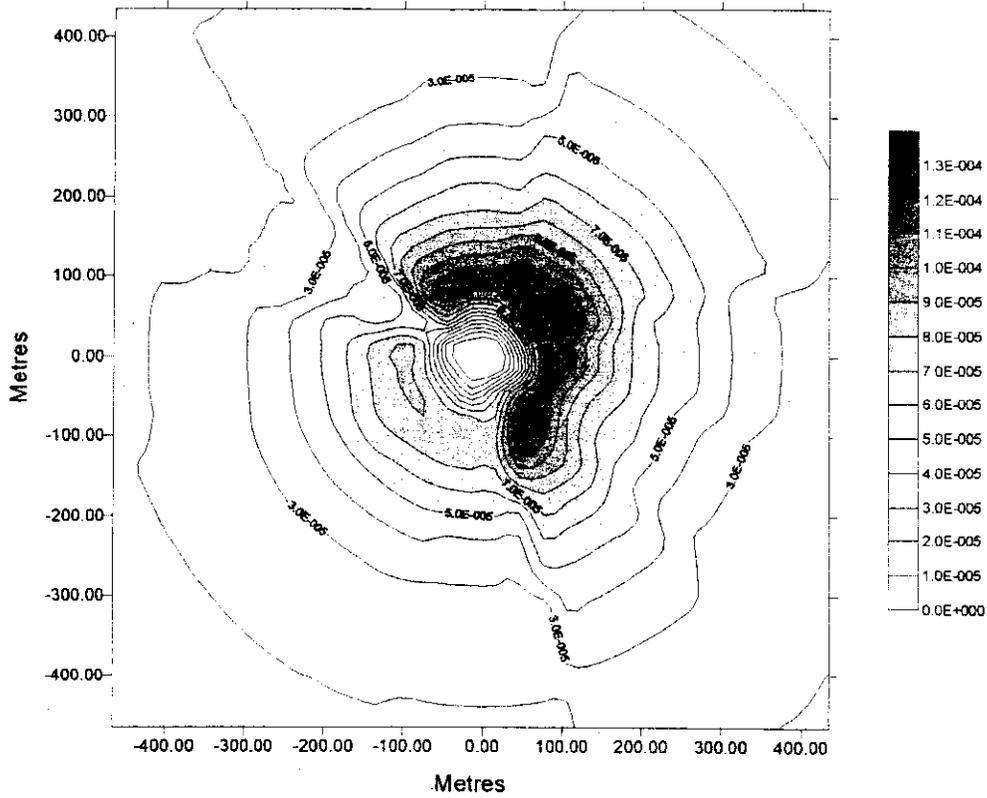


FIGURE 8(q) 99th percentiles of concentration for Shawbury, winter day run, short stack, pollutant: SO<sub>2</sub>

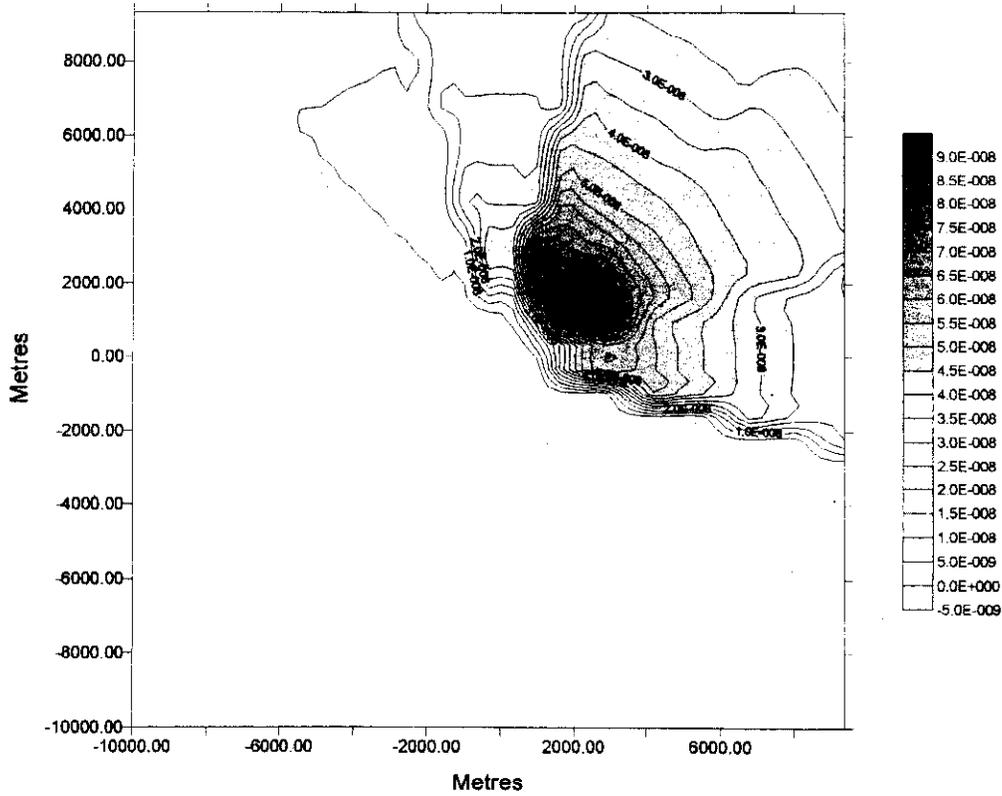


FIGURE 8(r) 99th percentiles of concentration for Shawbury, winter day run, tall stack, pollutant: SO<sub>2</sub>

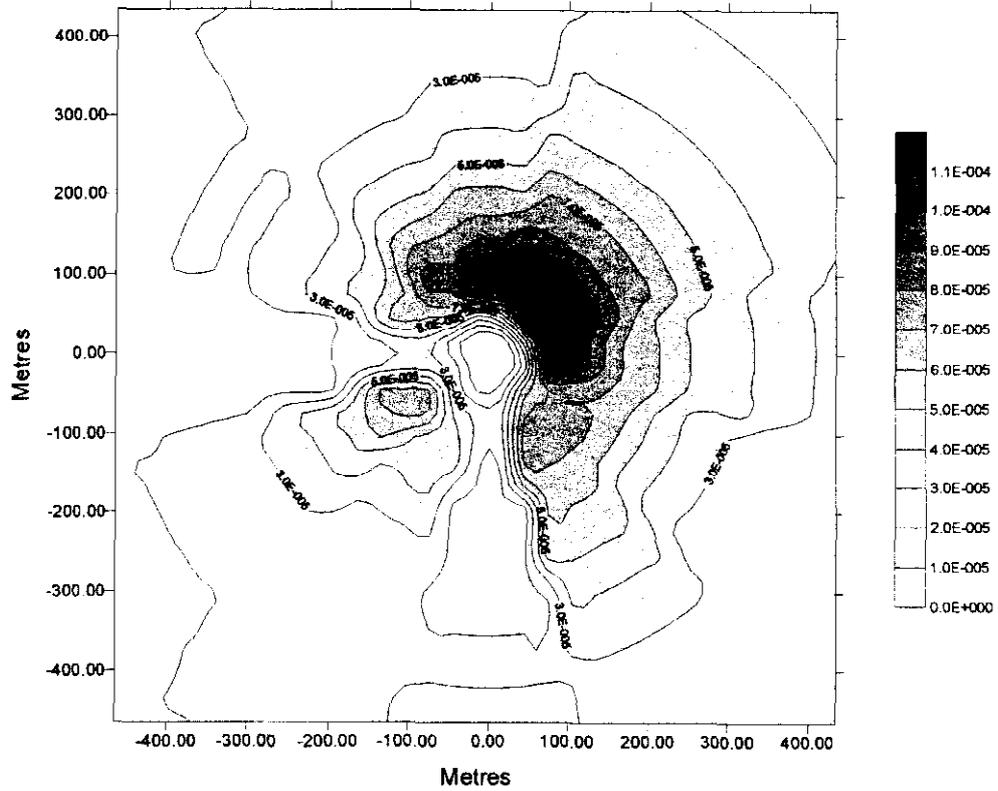


FIGURE 8(s) 99th percentiles of concentration for Shawbury, winter night run, short stack, pollutant: SO<sub>2</sub>

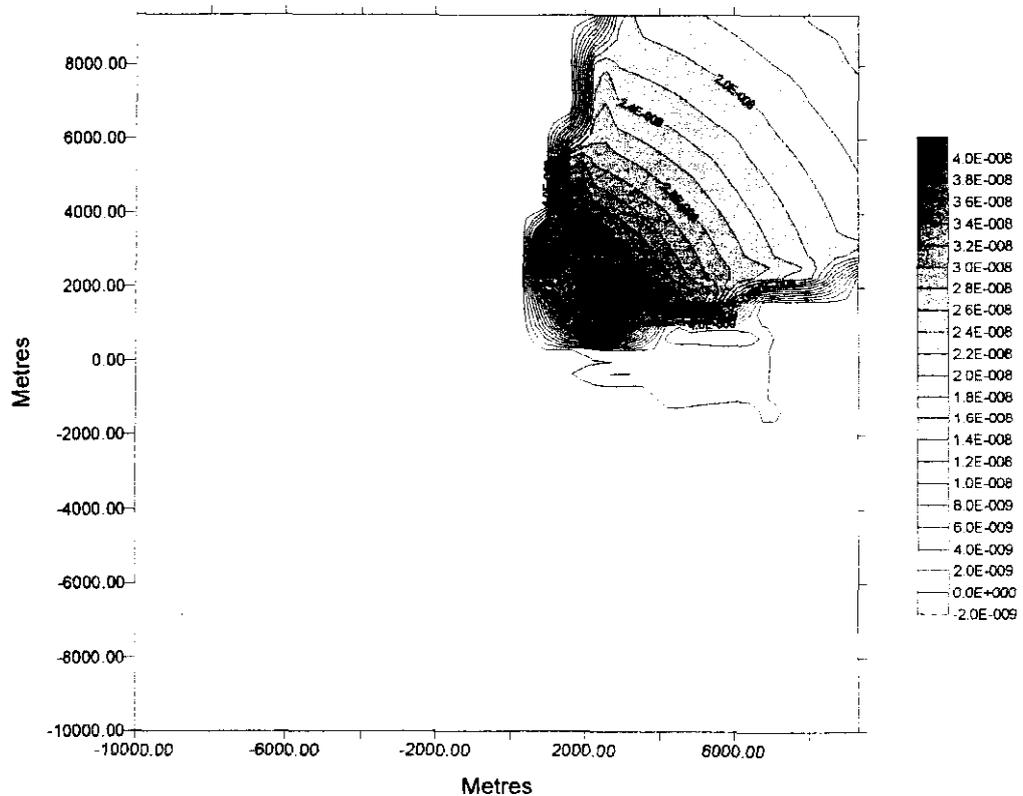
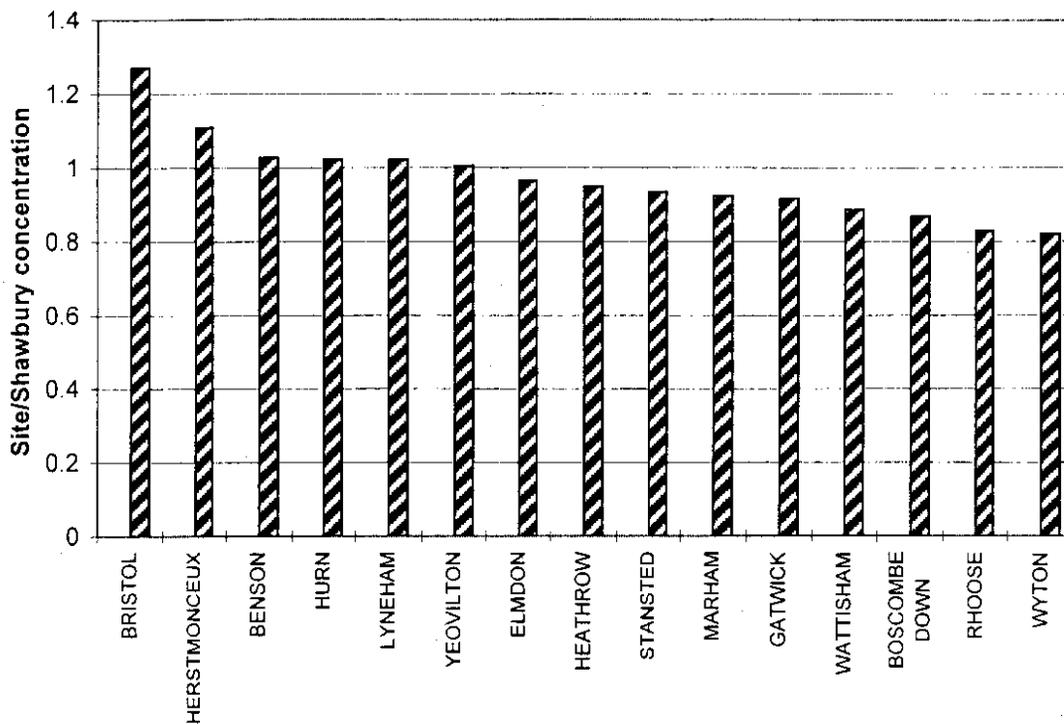
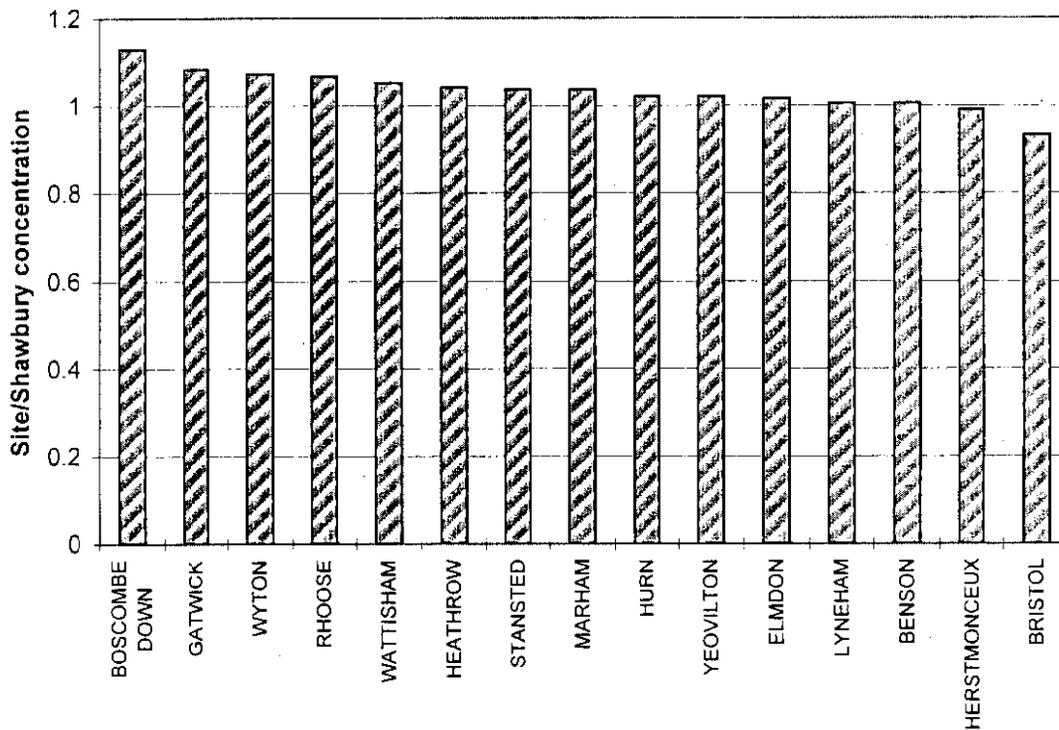


FIGURE 8(t) 99th percentiles of concentration for Shawbury, winter night run, tall stack, pollutant: SO<sub>2</sub>



**FIGURE 9 Tall stack: annual mean concentration relative to Shawbury**



**FIGURE 10 Short stack: annual mean concentration relative to Shawbury**

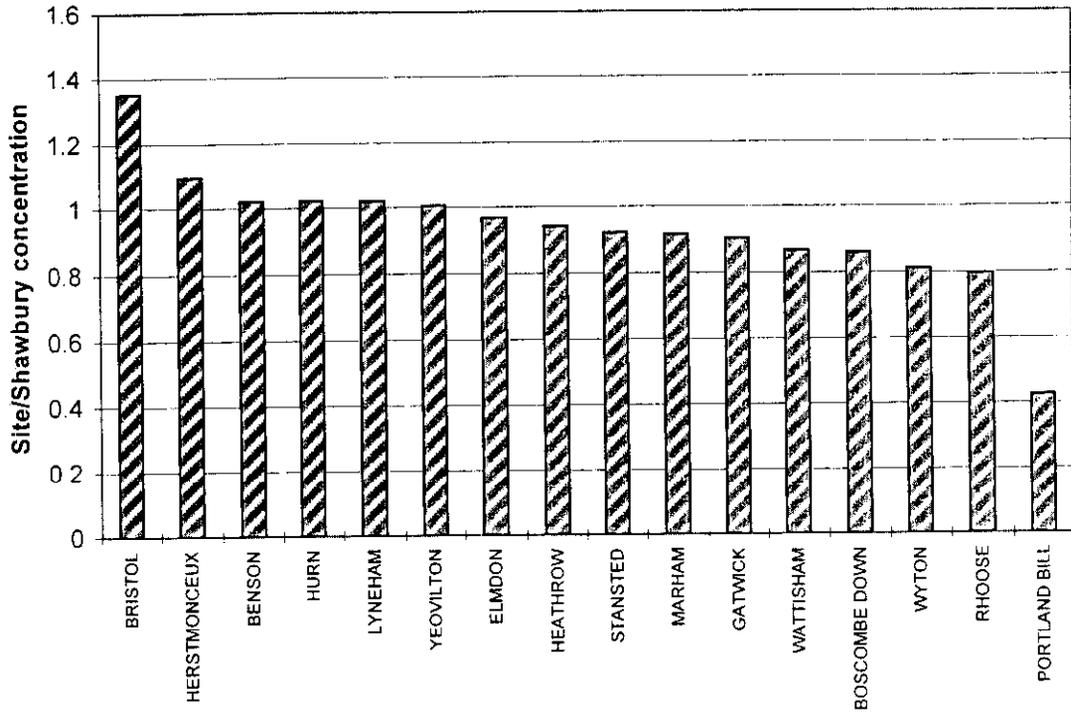


FIGURE 11 Tall stack: summer day mean concentration relative to Shawbury

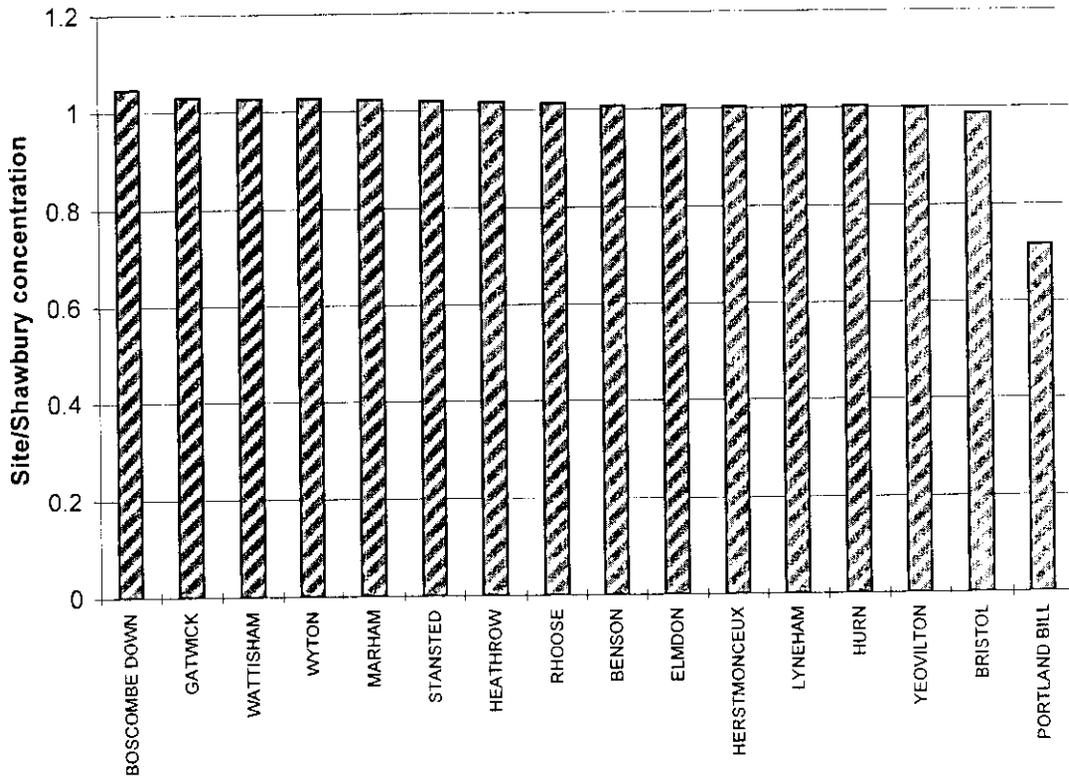


FIGURE 12 Short stack: summer day mean concentration relative to Shawbury

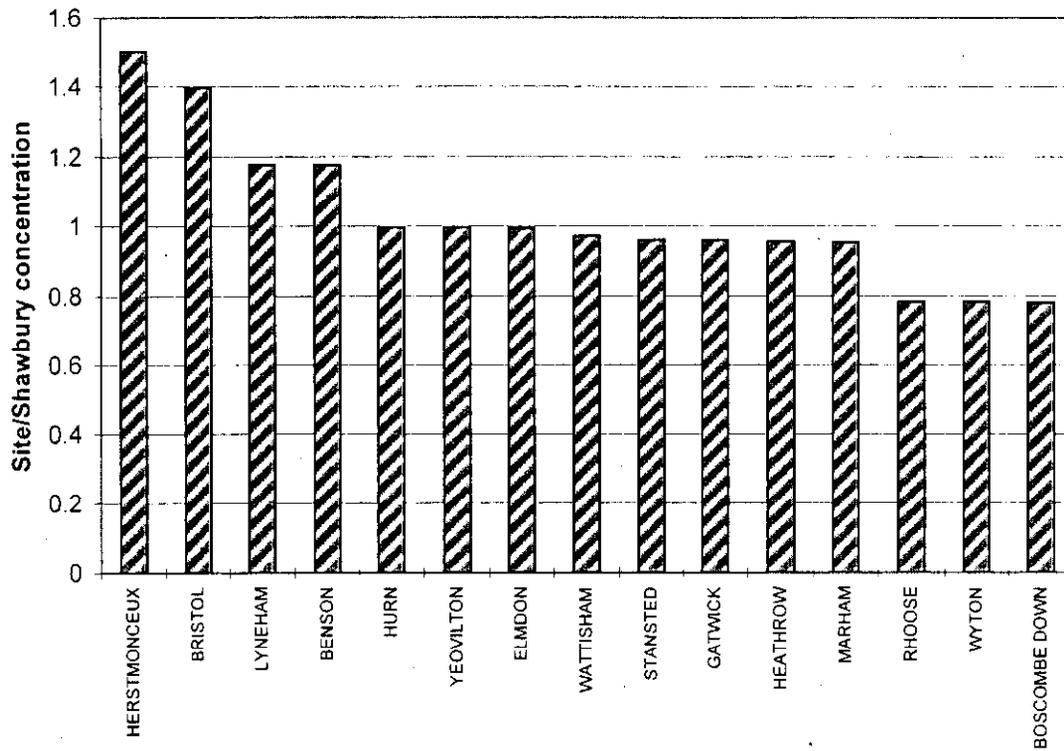


FIGURE 13 Tall stack: summer night mean concentration relative to Shawbury

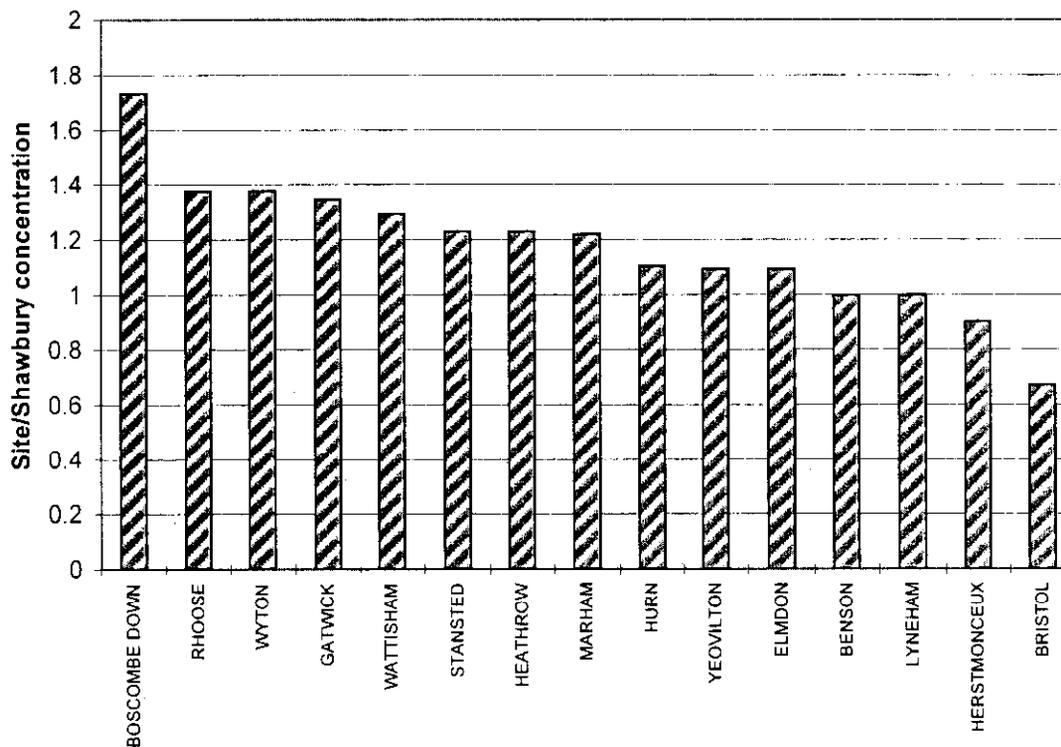


FIGURE 14 Short stack: summer night mean concentration relative to Shawbury

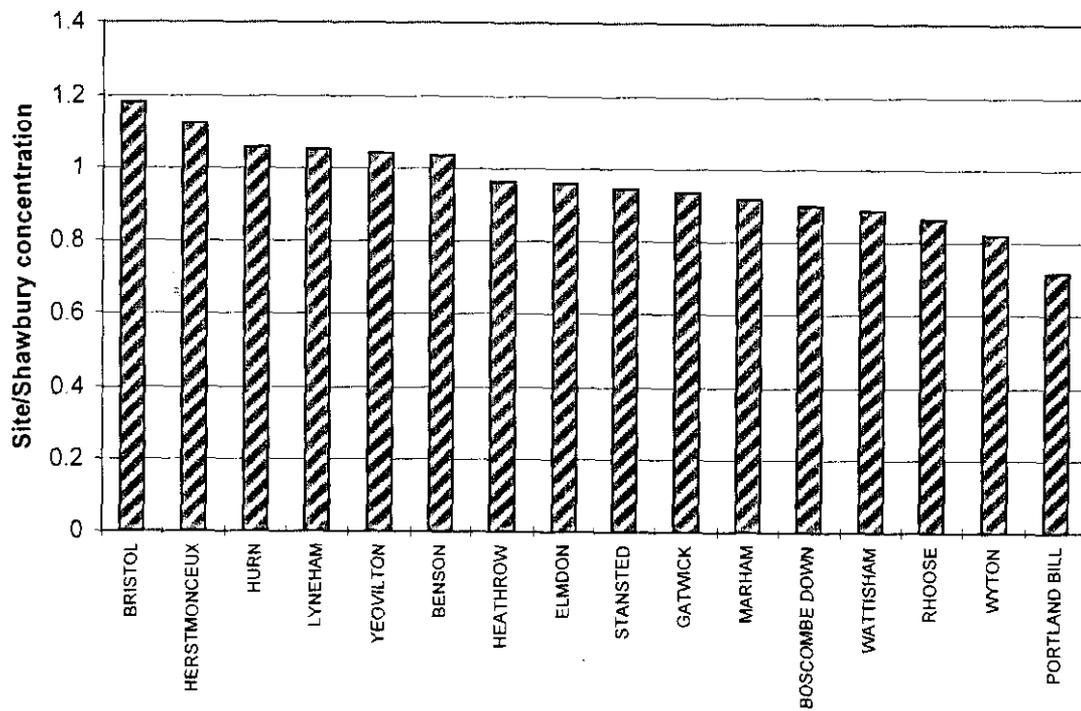


FIGURE 15 Tall stack: winter day mean concentration relative to Shawbury

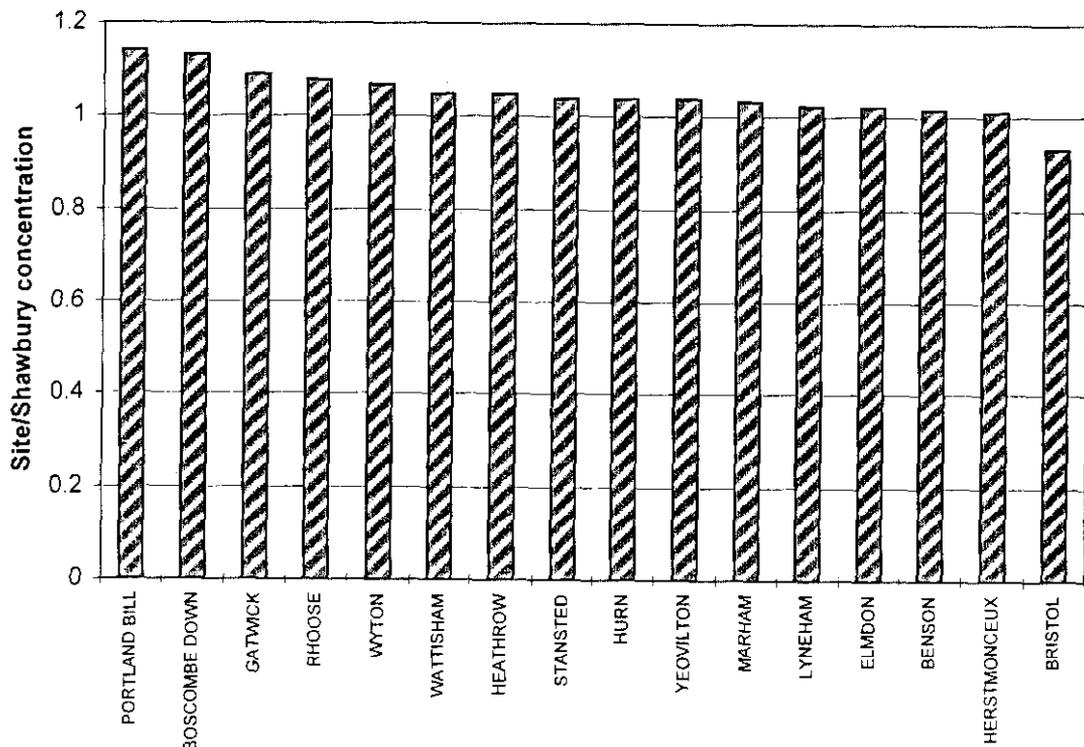


FIGURE 16 Short stack: winter day mean concentration relative to Shawbury

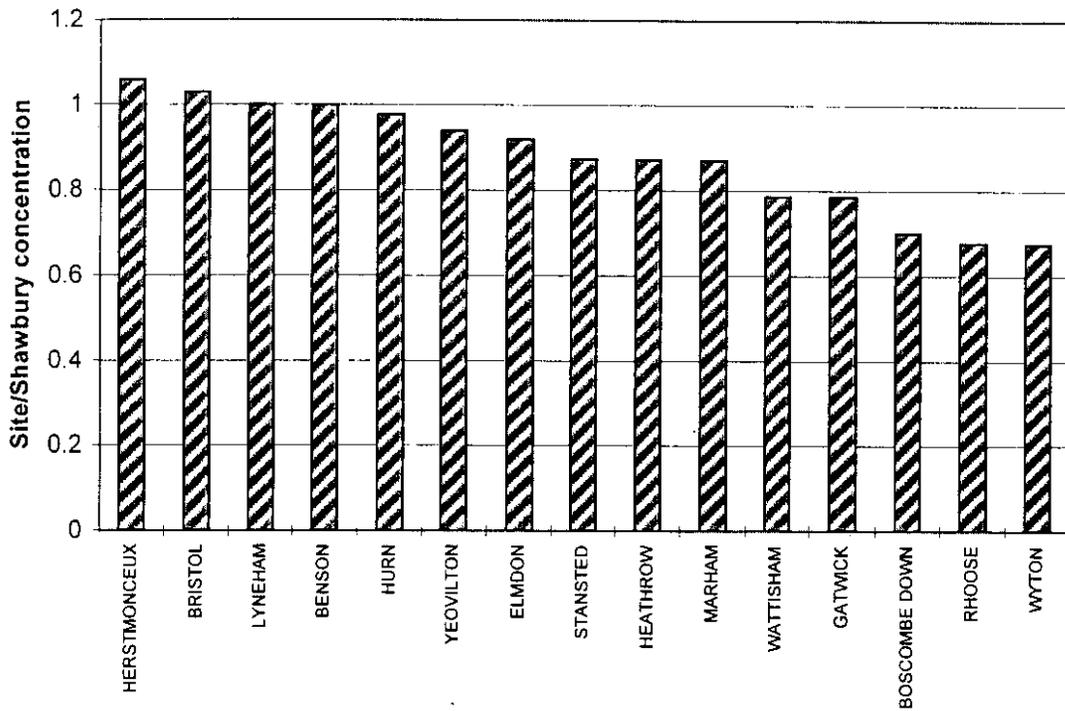


FIGURE 17 Tall stack: winter night mean concentration relative to Shawbury

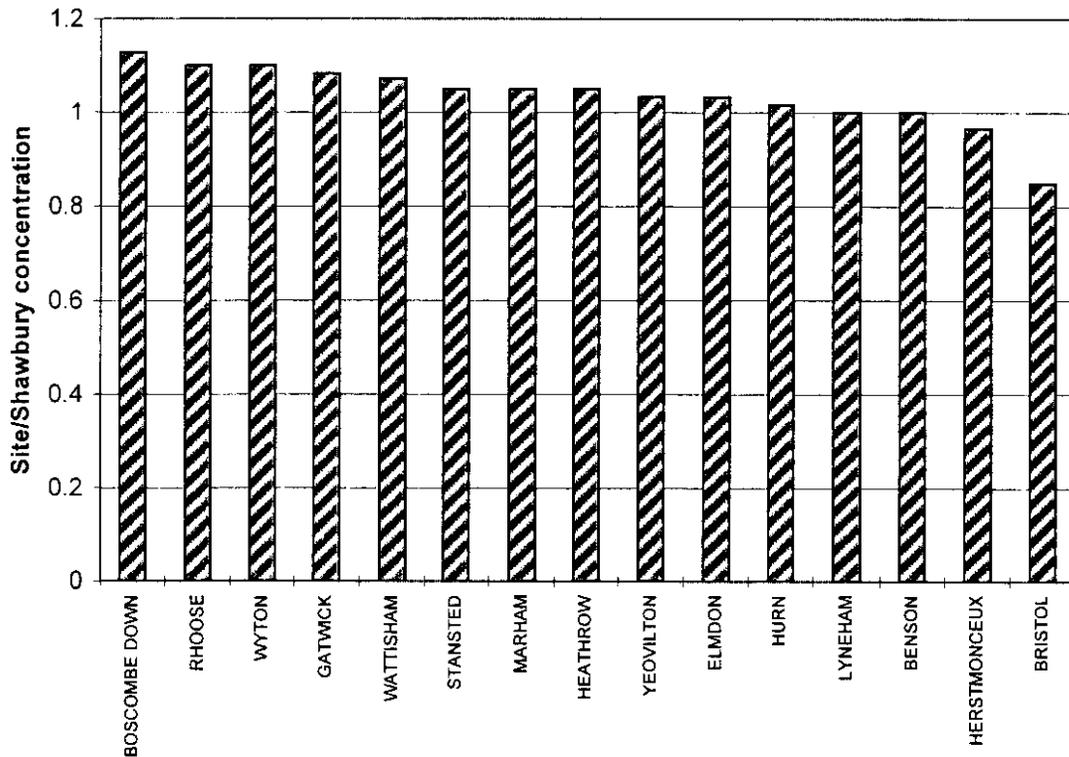


FIGURE 18 Short stack: winter night mean concentration relative to Shawbury

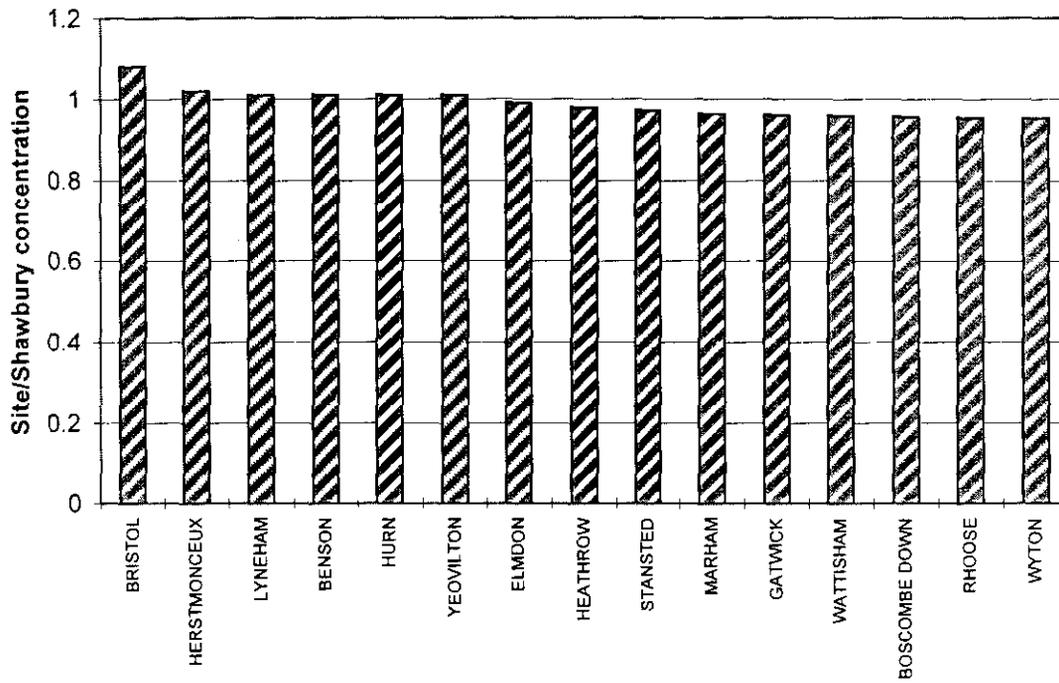


FIGURE 19 Tall stack: annual 99th percentile concentration relative to Shawbury

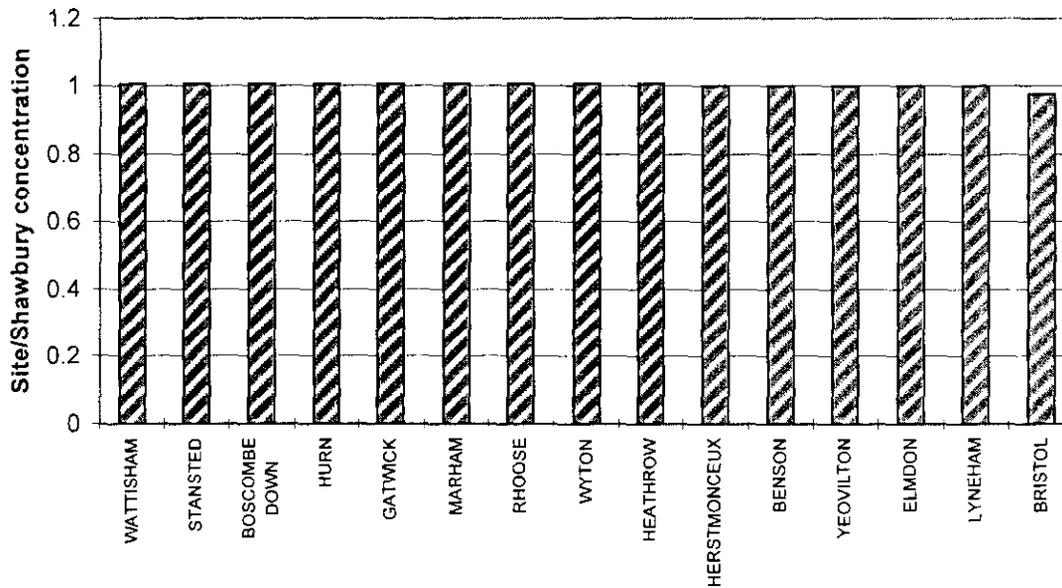
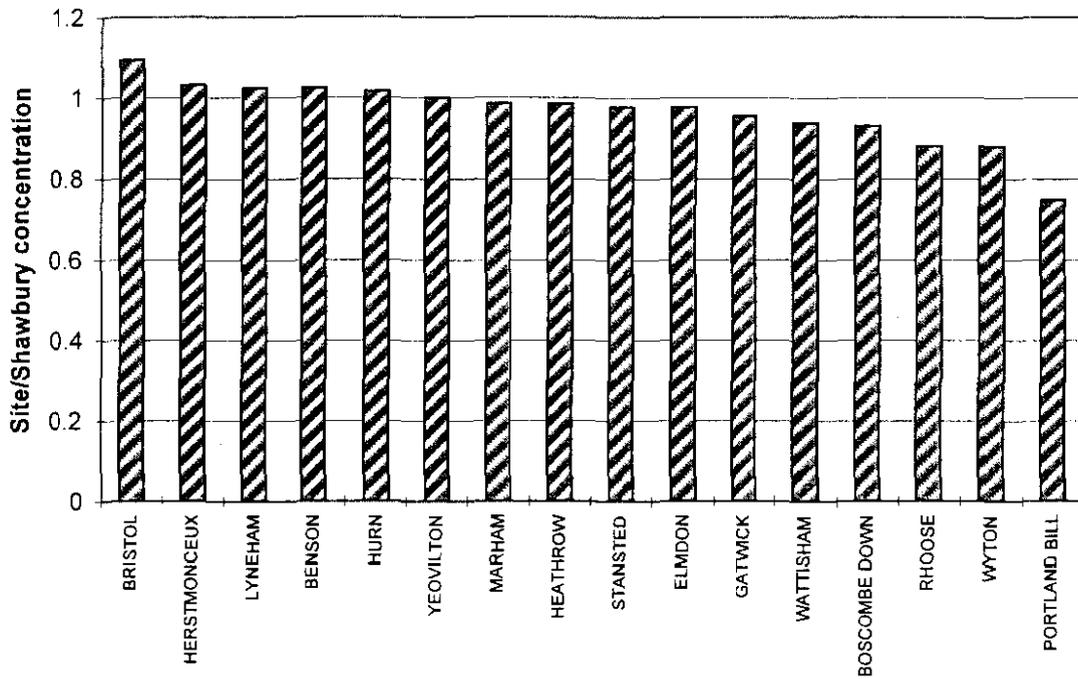
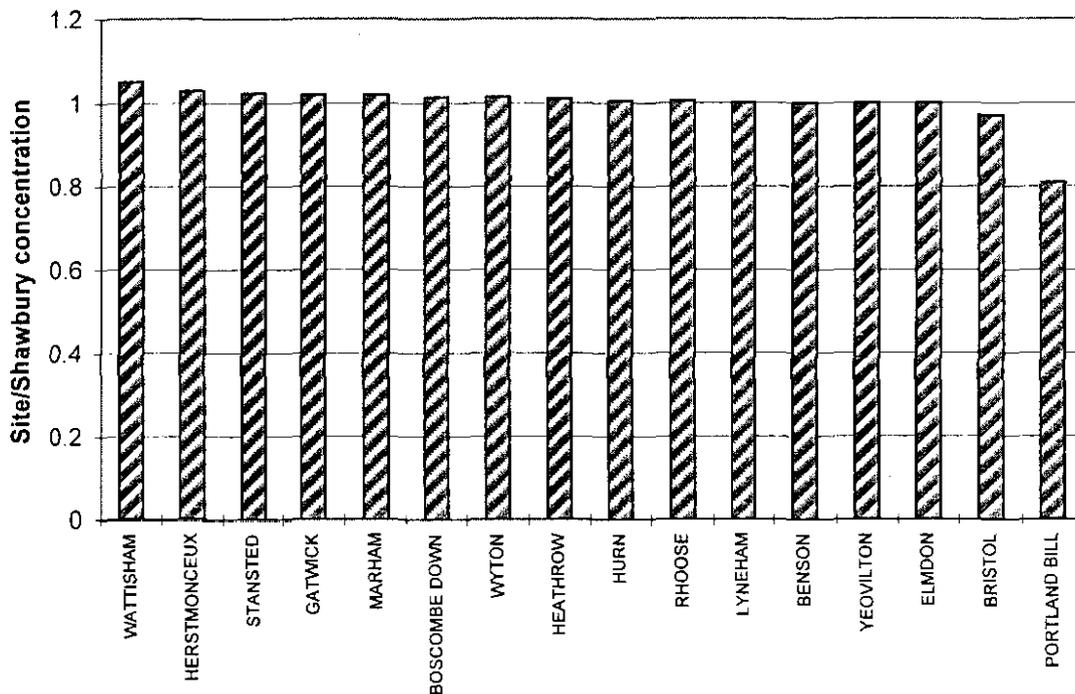


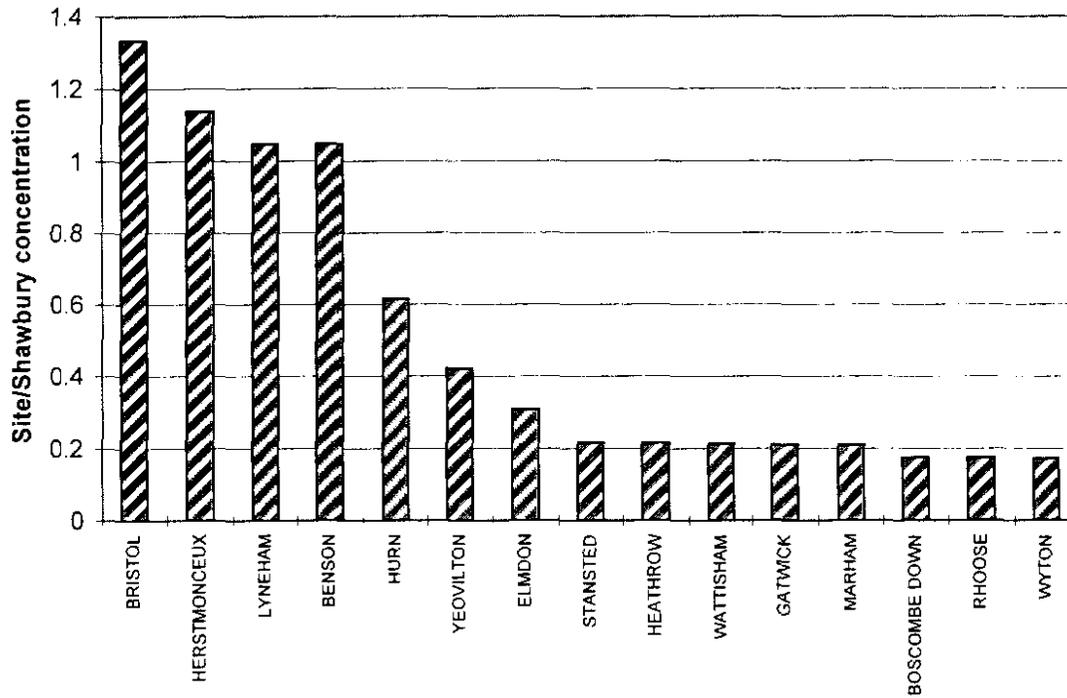
FIGURE 20 Short stack: annual 99th percentile concentration relative to Shawbury



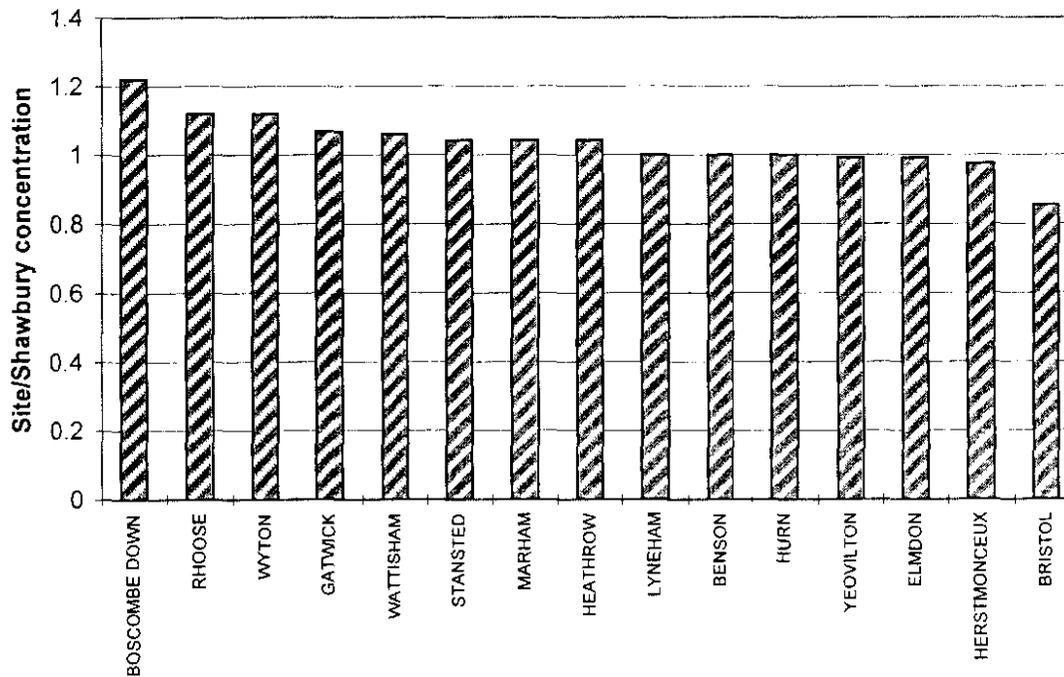
**FIGURE 21 Tall stack: summer day 99th percentile concentration relative to Shawbury**



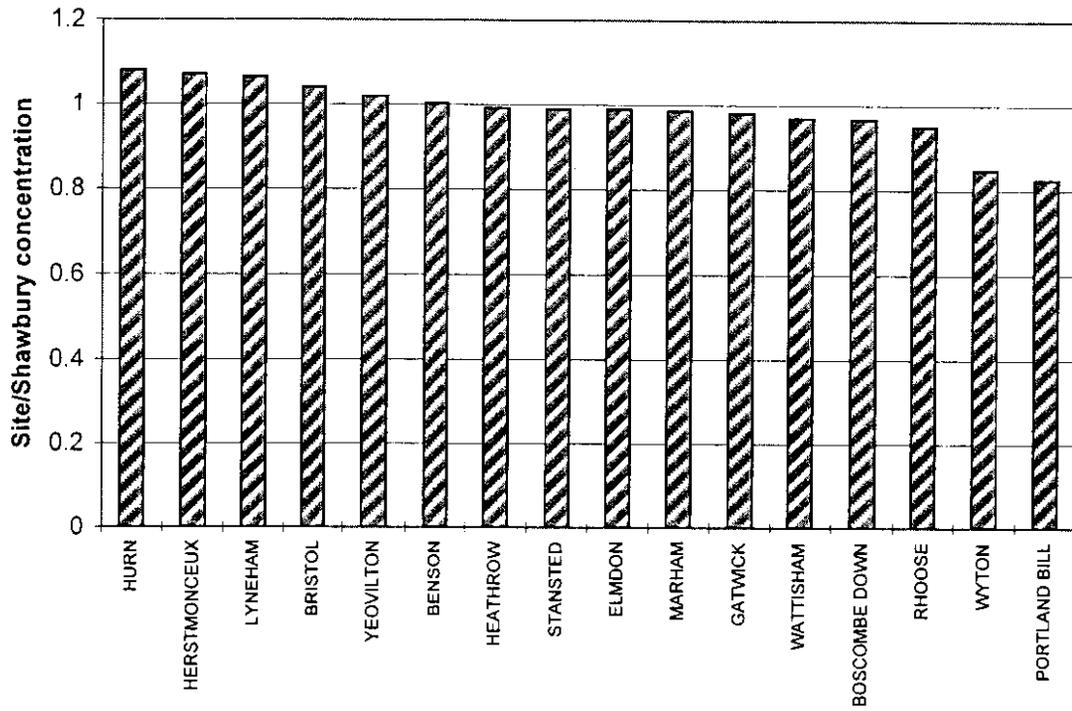
**FIGURE 22 Short stack: summer day 99th percentile concentration relative to Shawbury**



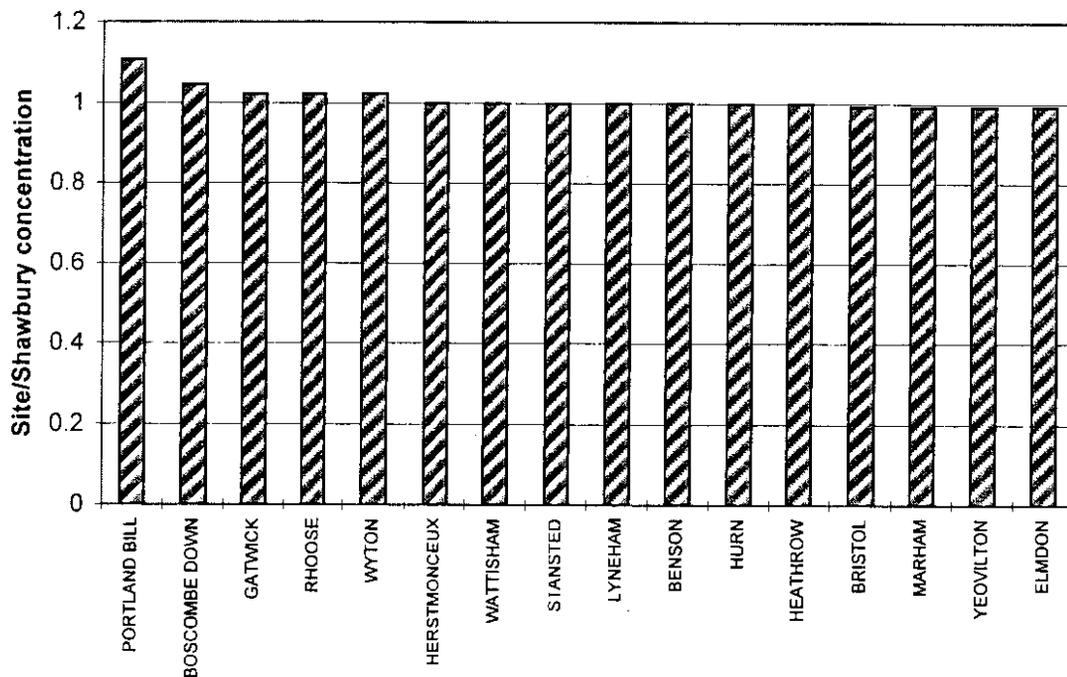
**FIGURE 23 Tall stack: summer night 99th percentile concentration relative to Shawbury**



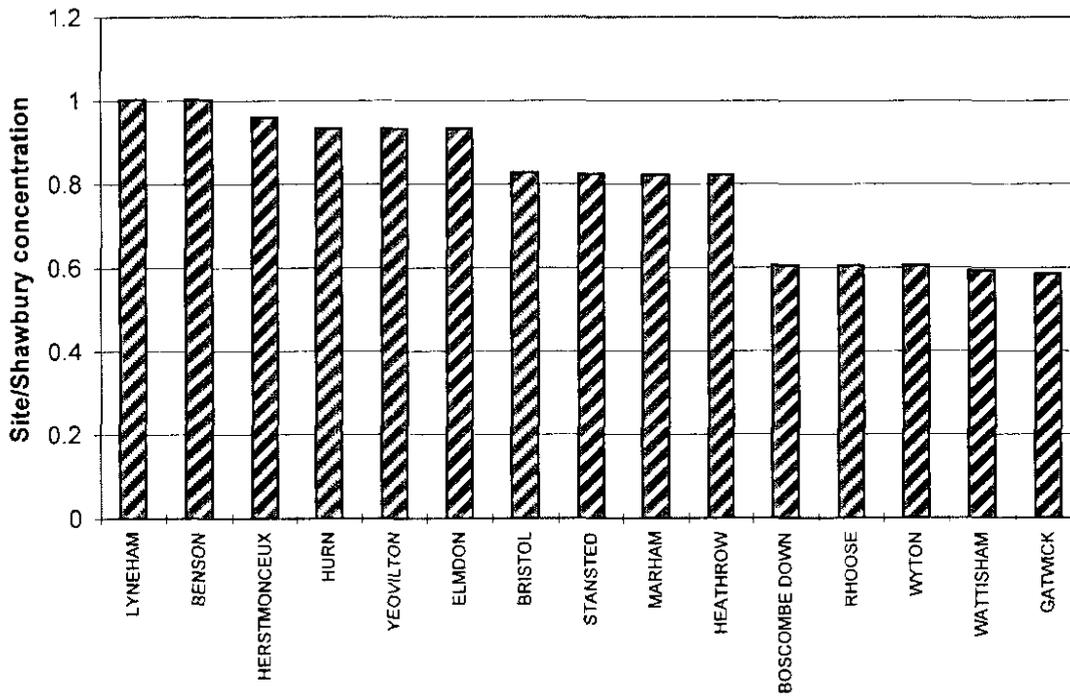
**FIGURE 24 Short stack: summer night 99th percentile concentration relative to Shawbury**



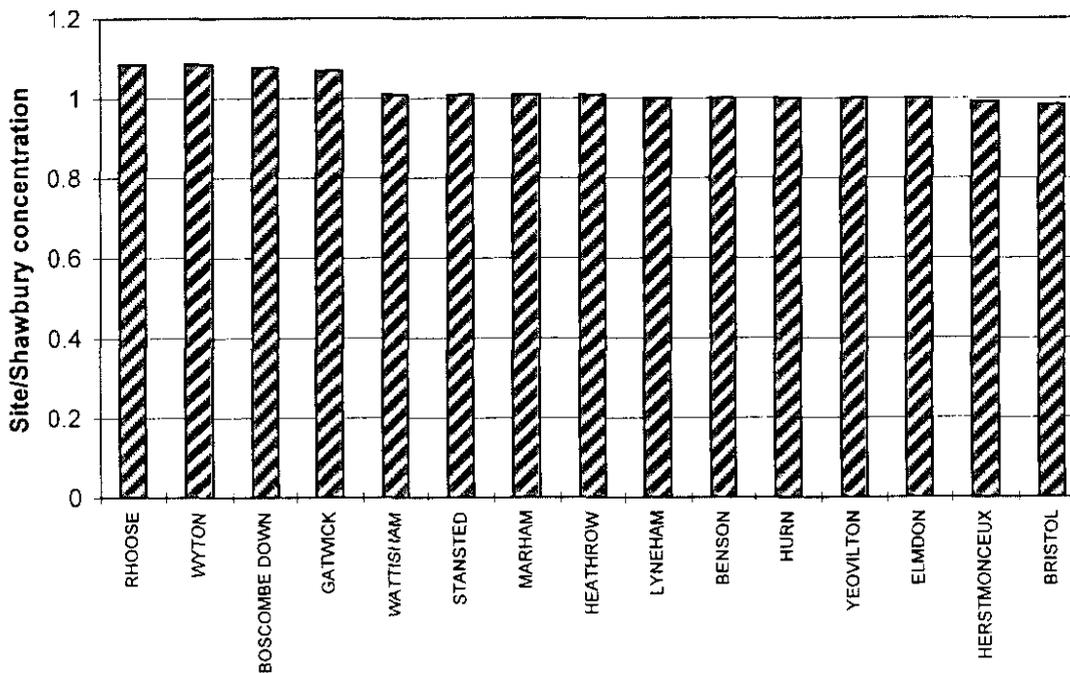
**FIGURE 25 Tall stack: winter day 99th percentile concentration relative to Shawbury**



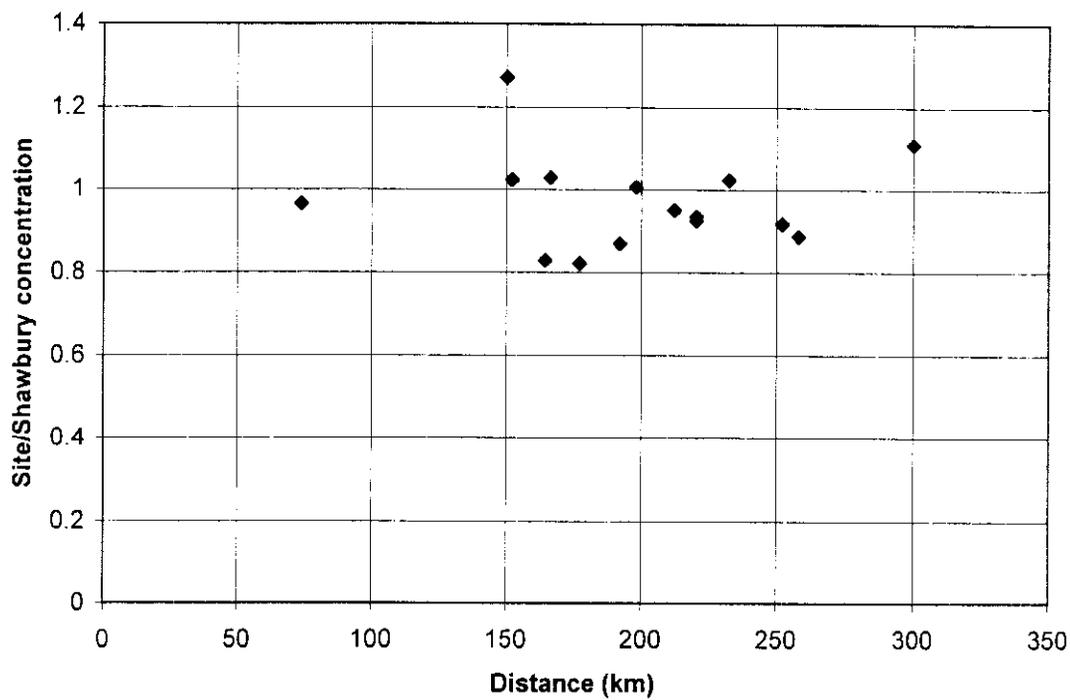
**FIGURE 26 Short stack: winter day 99th percentile concentration relative to Shawbury**



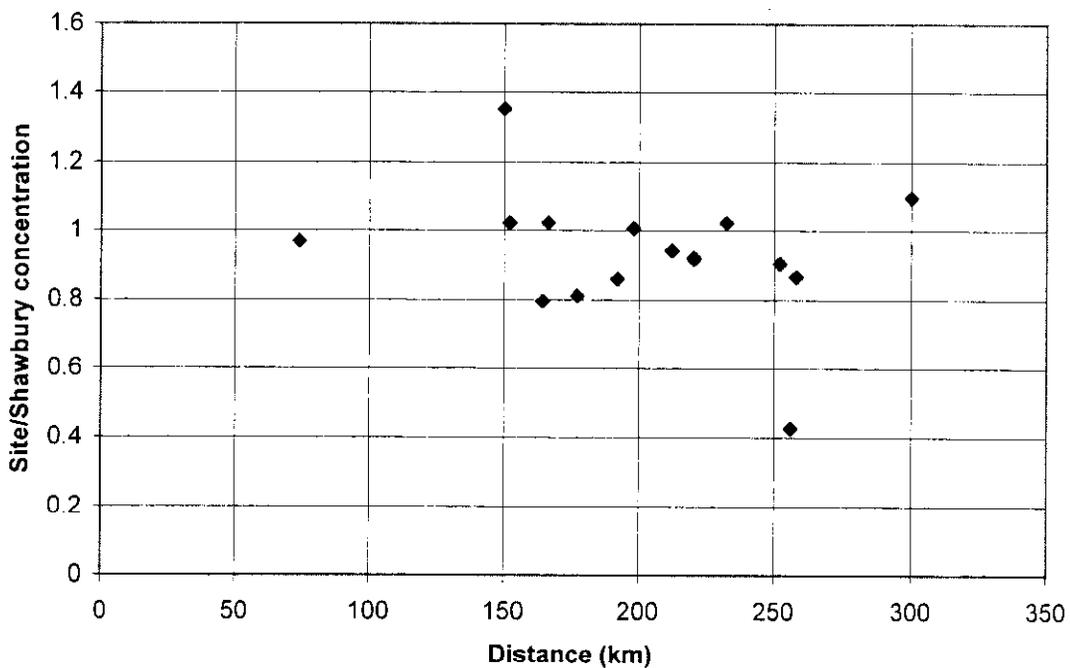
**FIGURE 27 Tall stack: winter night 99th percentile concentration relative to Shawbury**



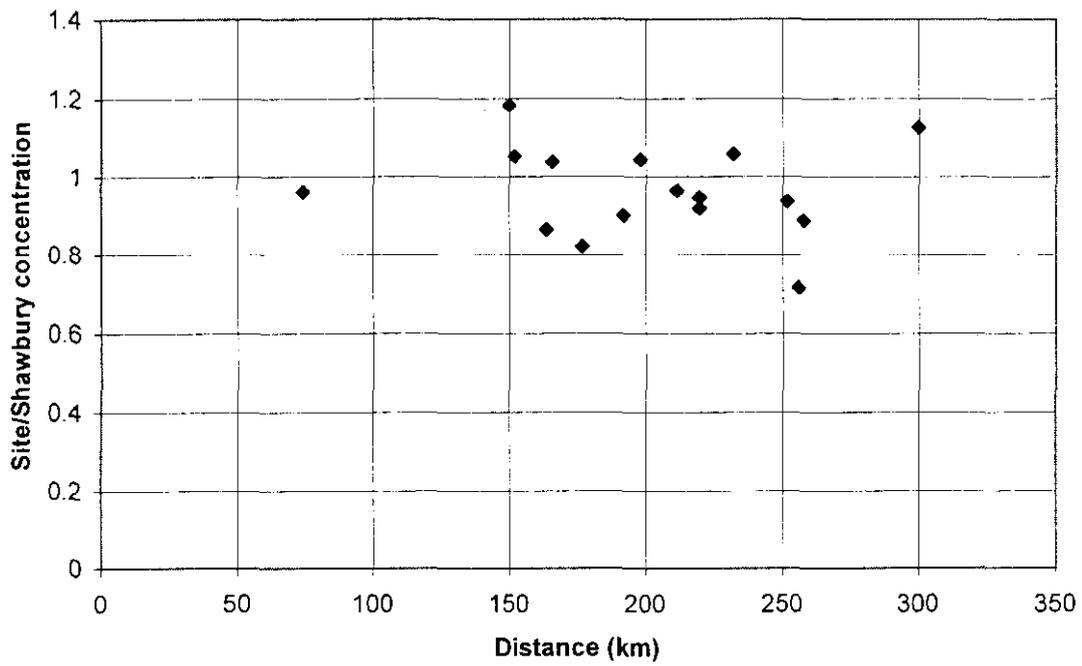
**FIGURE 28 Short stack: winter night 99th percentile concentration relative to Shawbury**



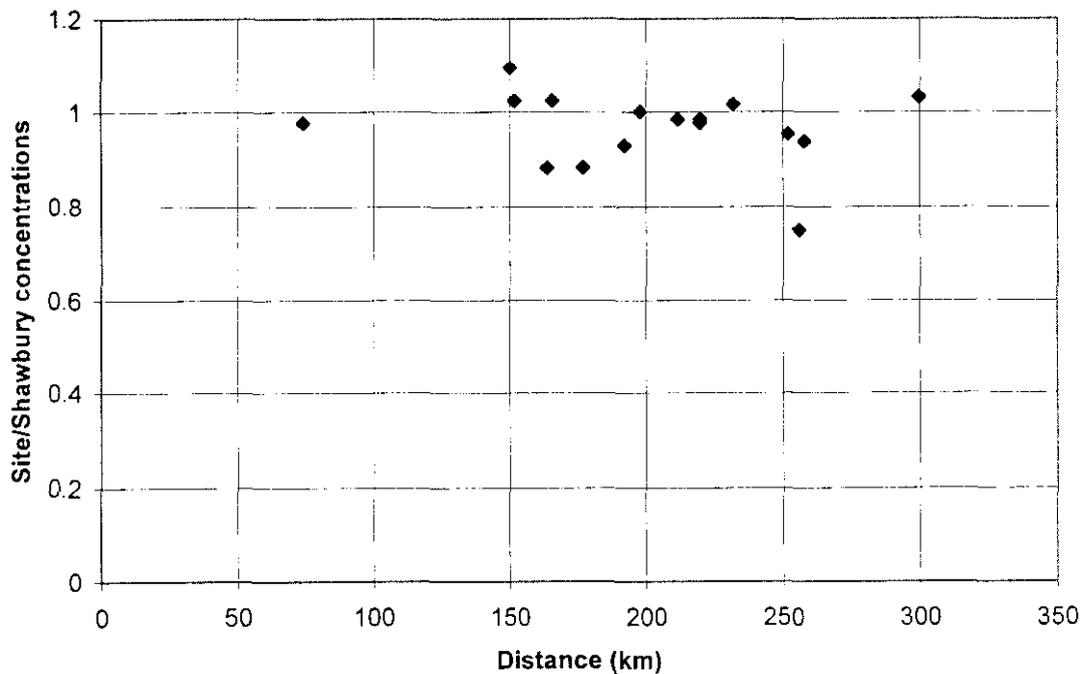
**FIGURE 29 Tall stack: annual mean concentration relative to Shawbury with distance from Shawbury**



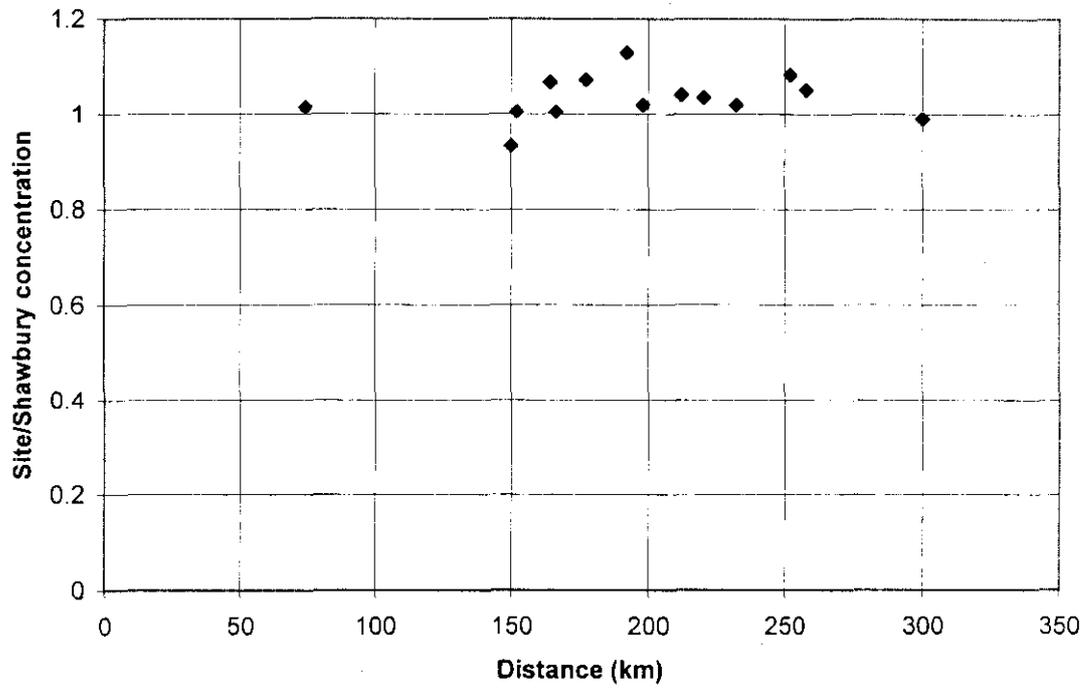
**FIGURE 30 Tall stack: summer day mean concentration relative to Shawbury with distance from Shawbury**



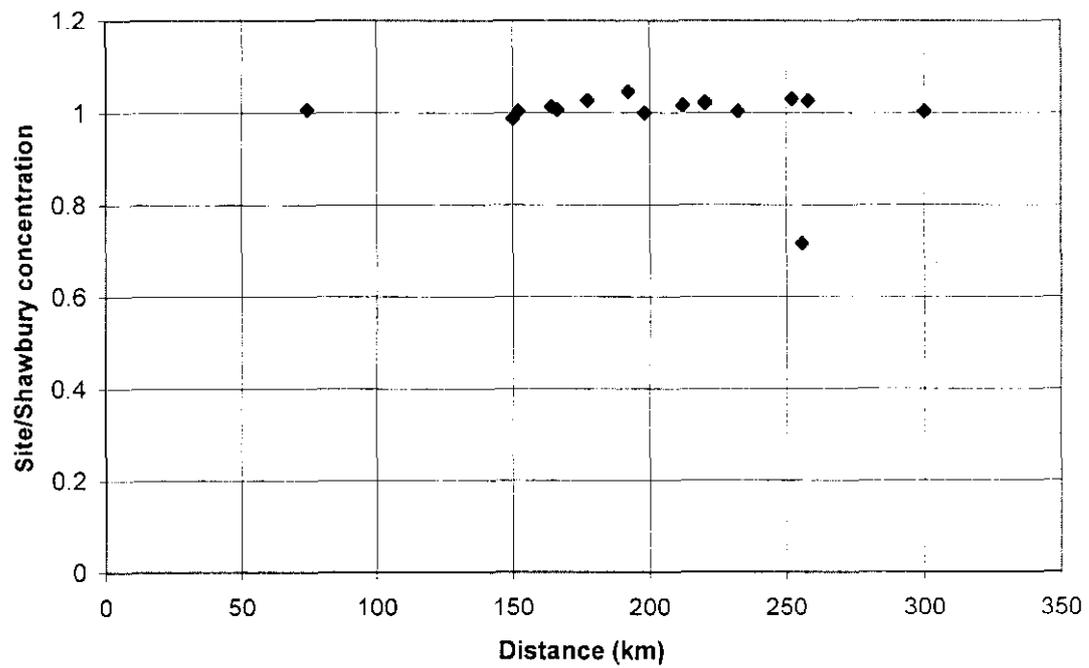
**FIGURE 31 Tall stack: winter day mean concentration relative to Shawbury with distance from Shawbury**



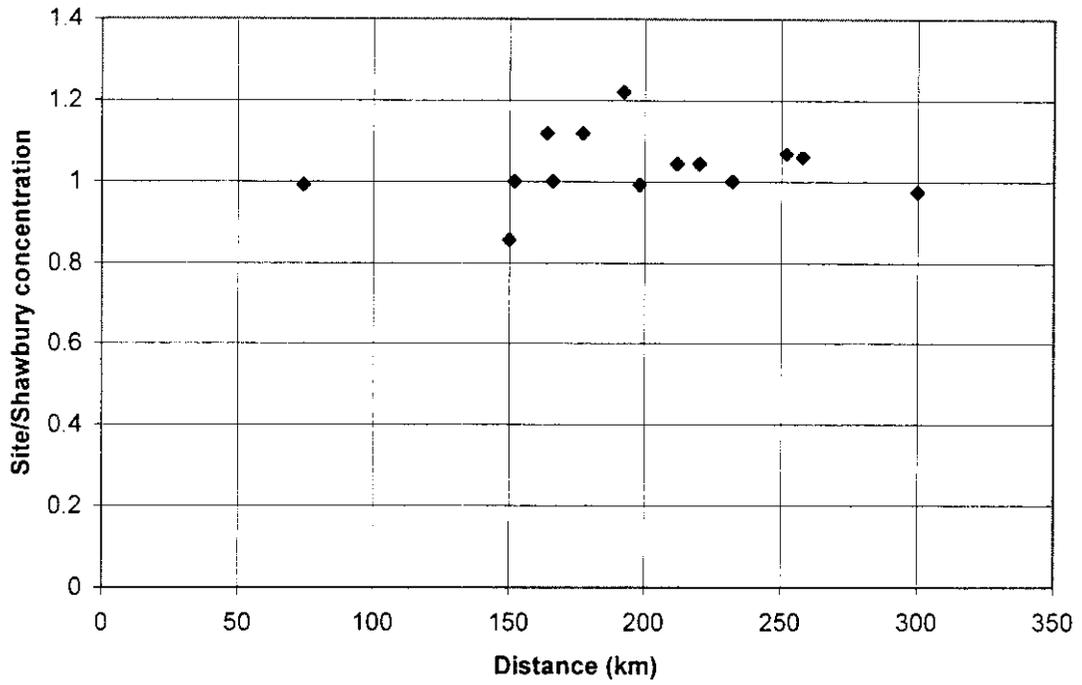
**FIGURE 32 Tall stack: summer day 99th percentile concentration relative to Shawbury with distance from Shawbury**



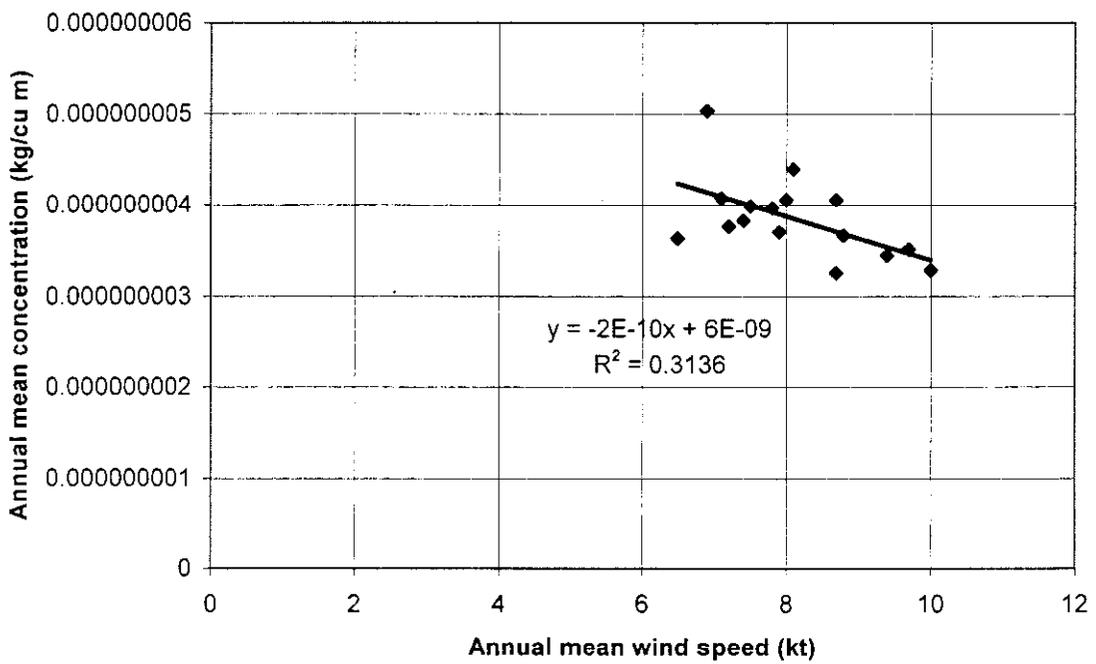
**FIGURE 33 Short stack: annual mean concentration relative to Shawbury with distance from Shawbury**



**FIGURE 34 Short stack: summer day mean concentration relative to Shawbury with distance from Shawbury**



**FIGURE 35 Short stack: summer night 99th percentile concentration relative to Shawbury with distance from Shawbury**



**FIGURE 36 Tall stack: annual mean concentration and annual mean wind speed**

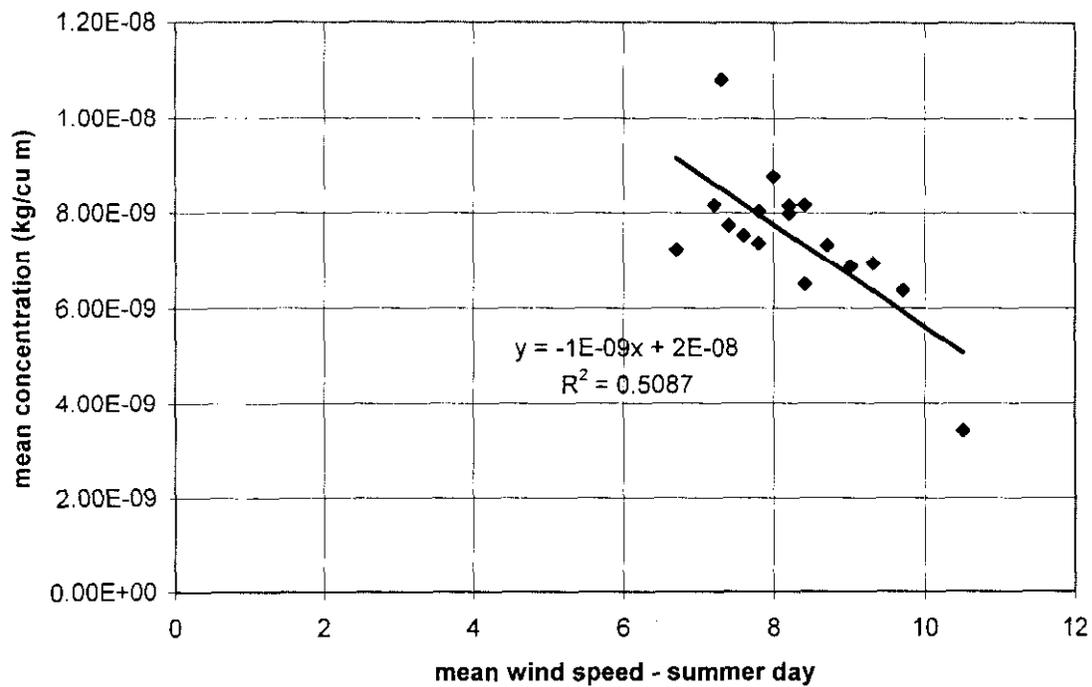


FIGURE 37 Tall stack: summer day mean concentration and summer day wind speed

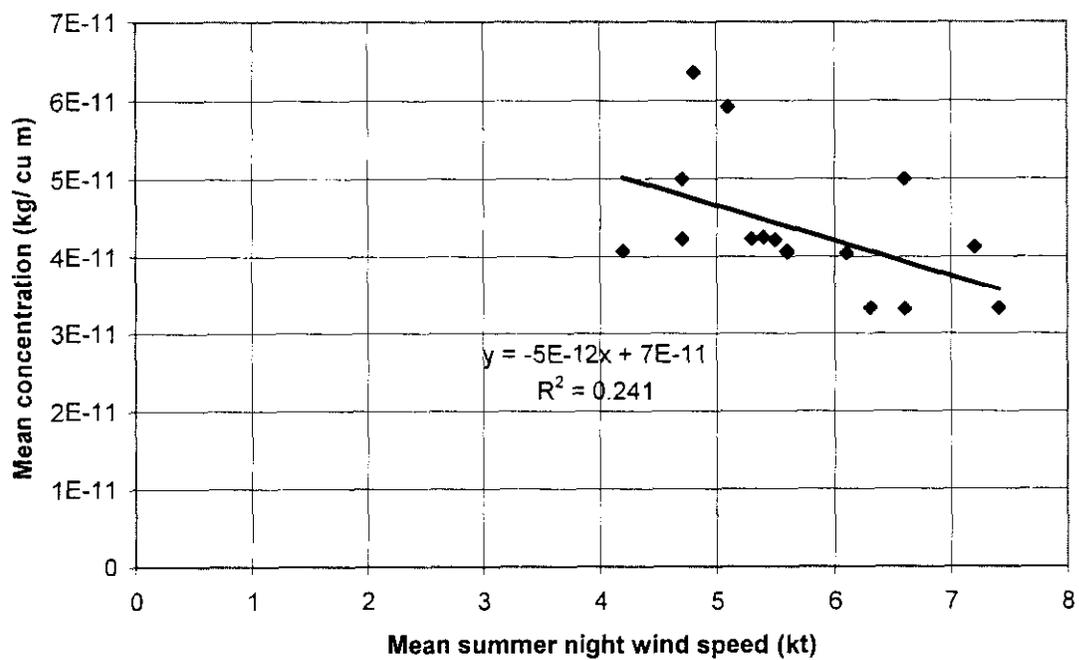


FIGURE 38 Tall stack: summer night mean concentration and mean wind speed

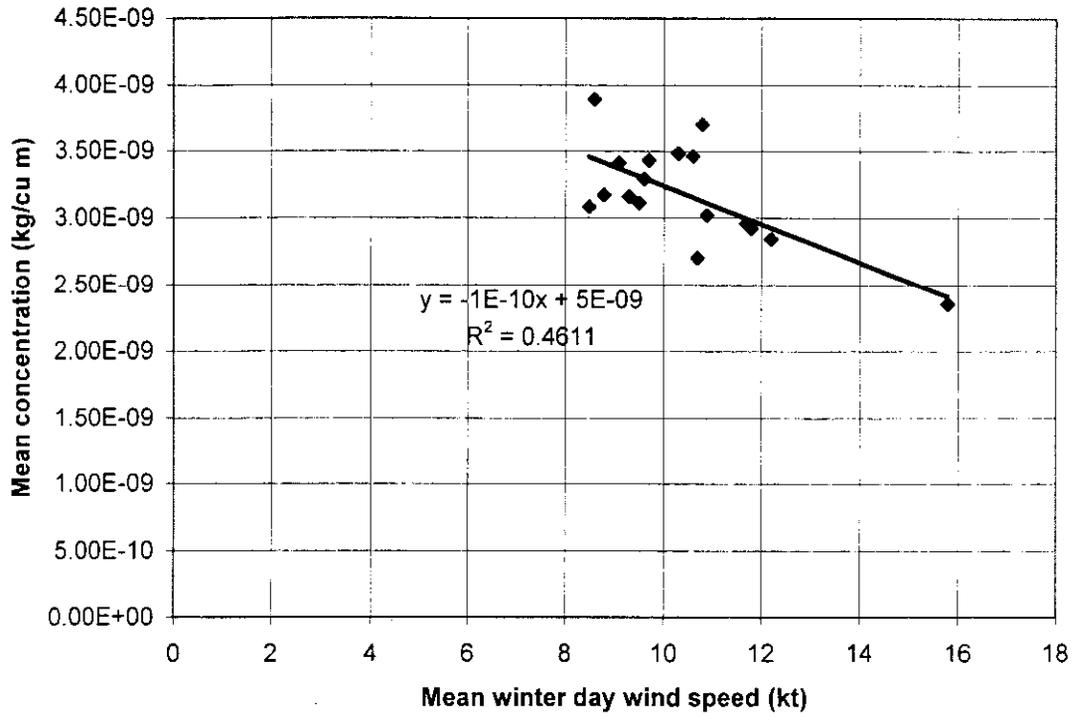


FIGURE 39 Tall stack: winter day mean concentration and mean wind speed

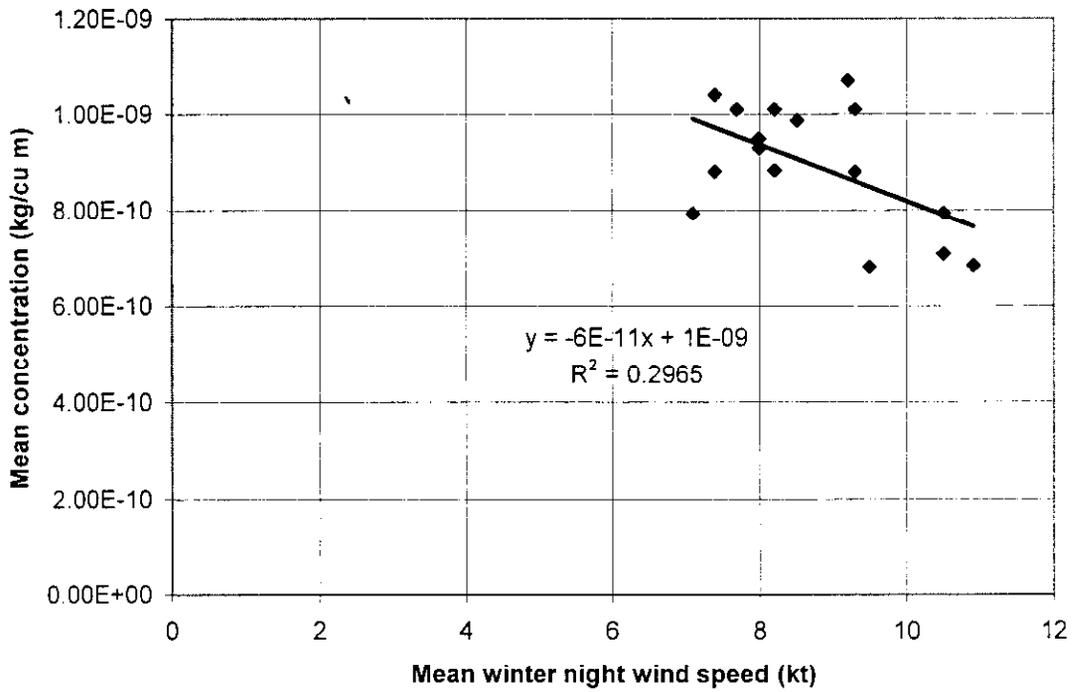


FIGURE 40 Tall stack: winter night mean concentration and mean wind speed

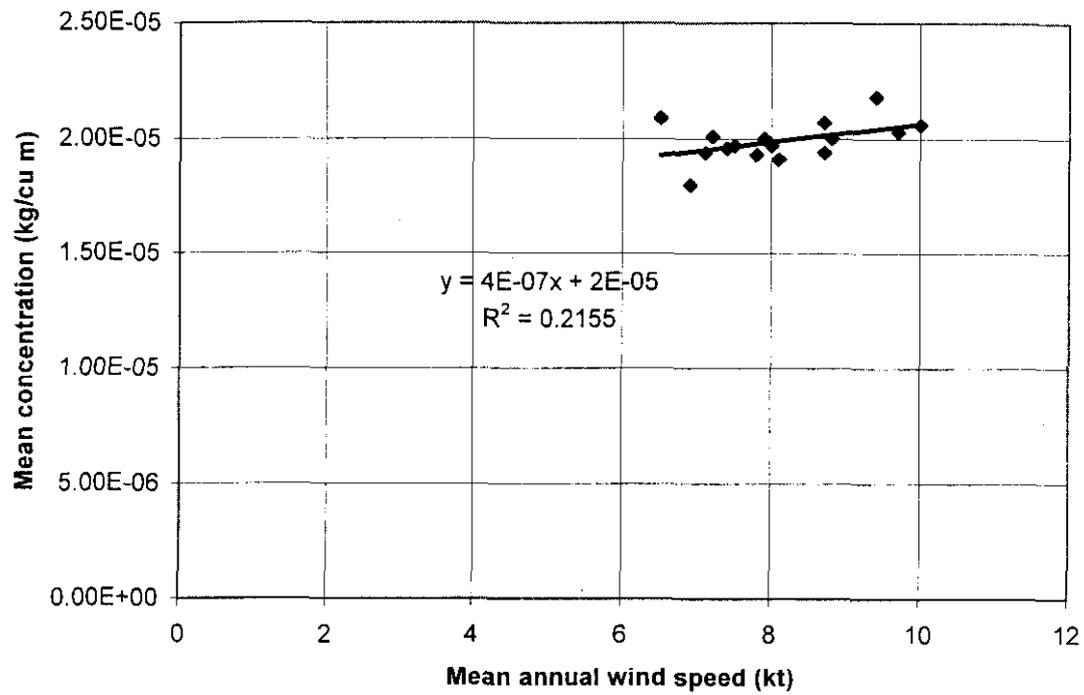


FIGURE 41 Short stack: mean annual concentration and mean annual wind speed

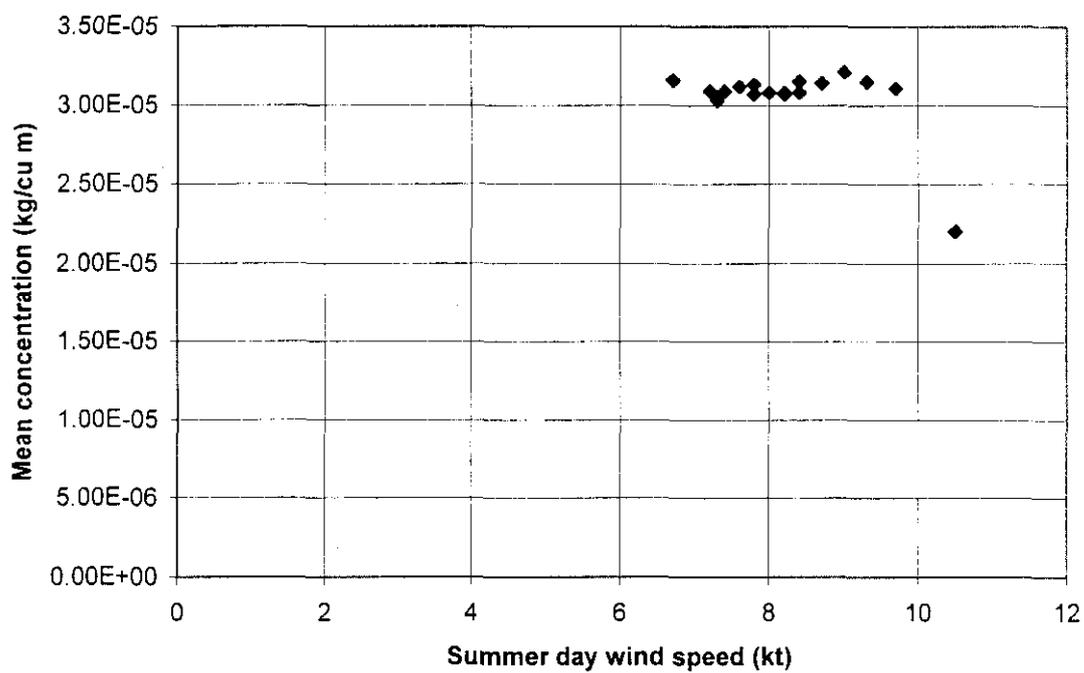


FIGURE 42 Short stack: summer day mean concentration and mean wind speed

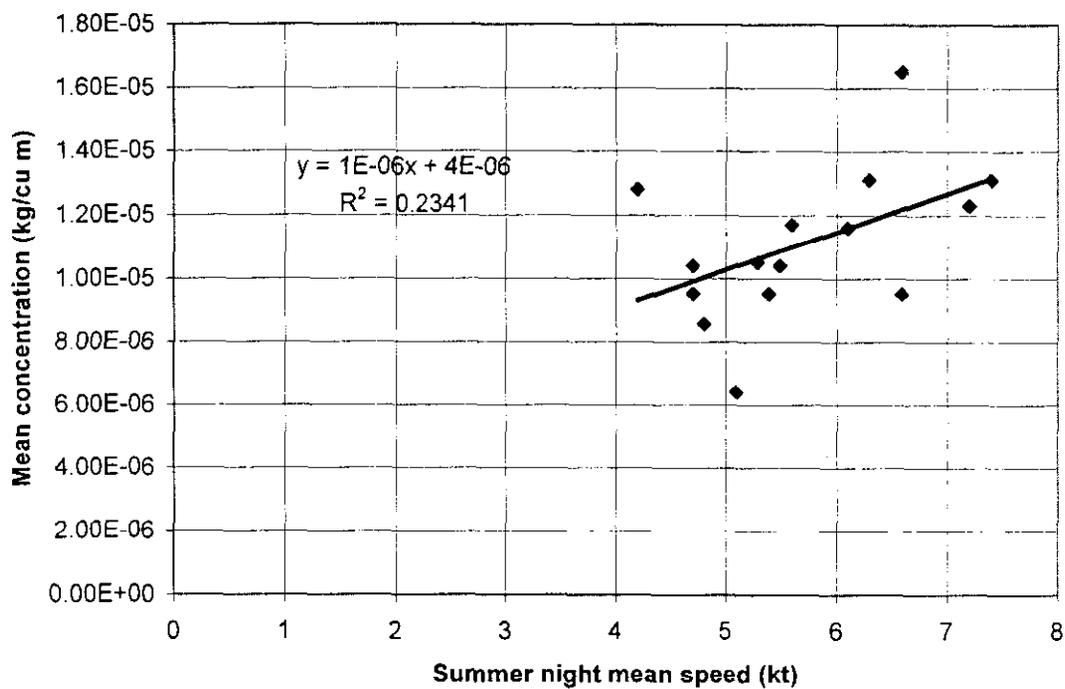


FIGURE 43 Short stack: summer night mean concentration and mean wind speed

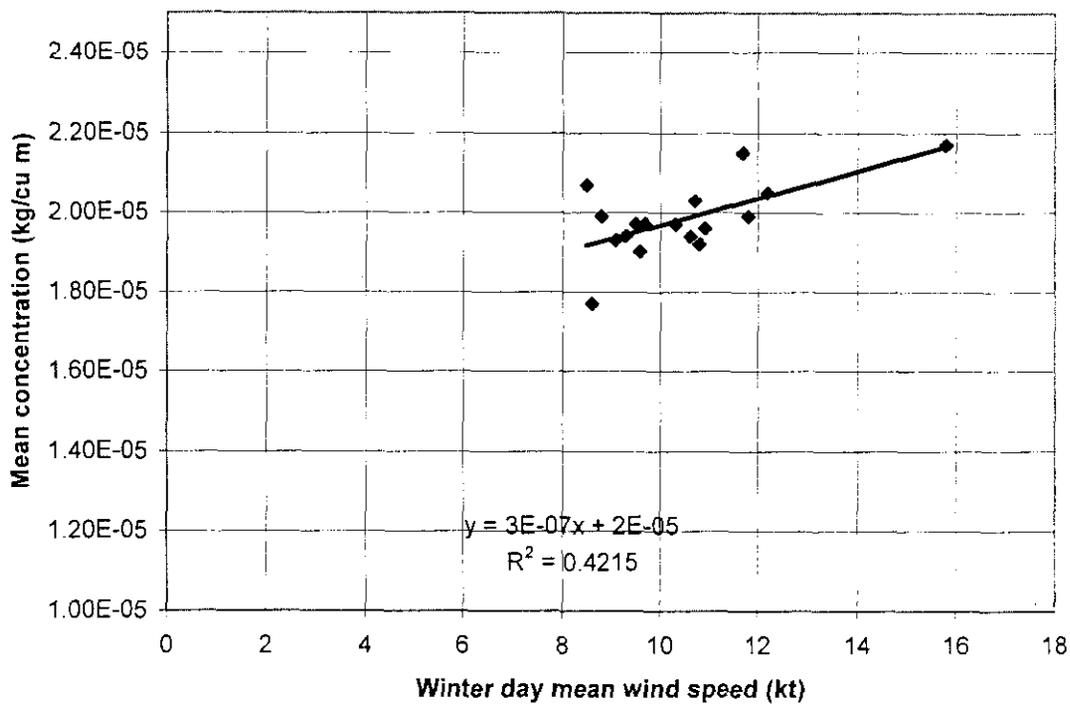
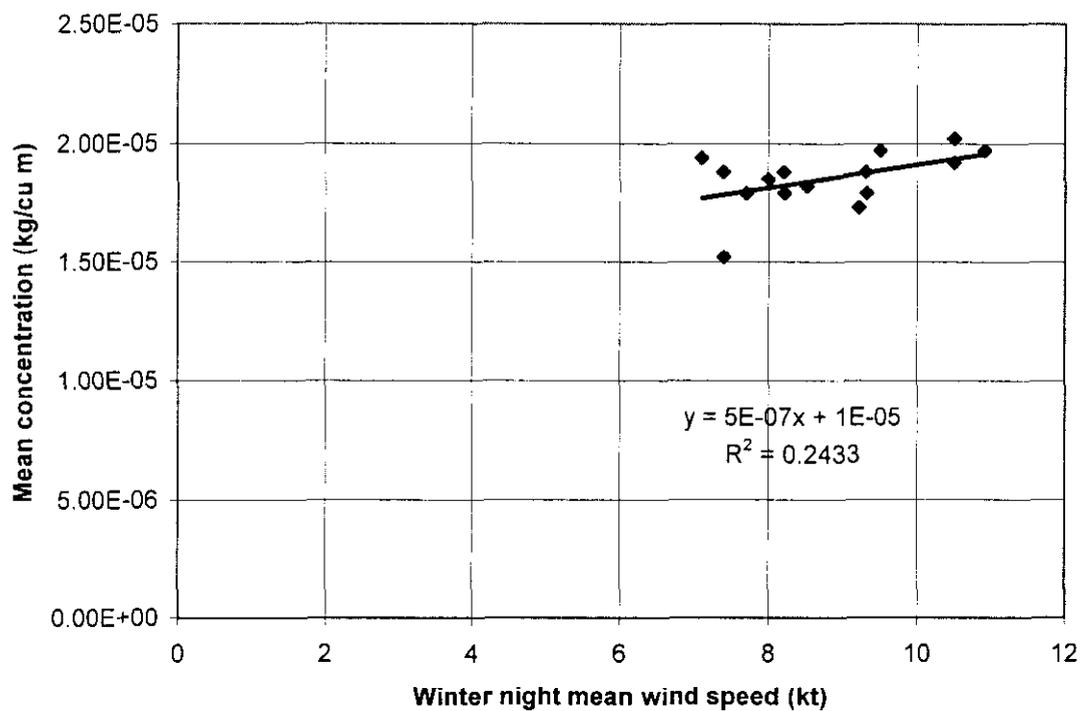
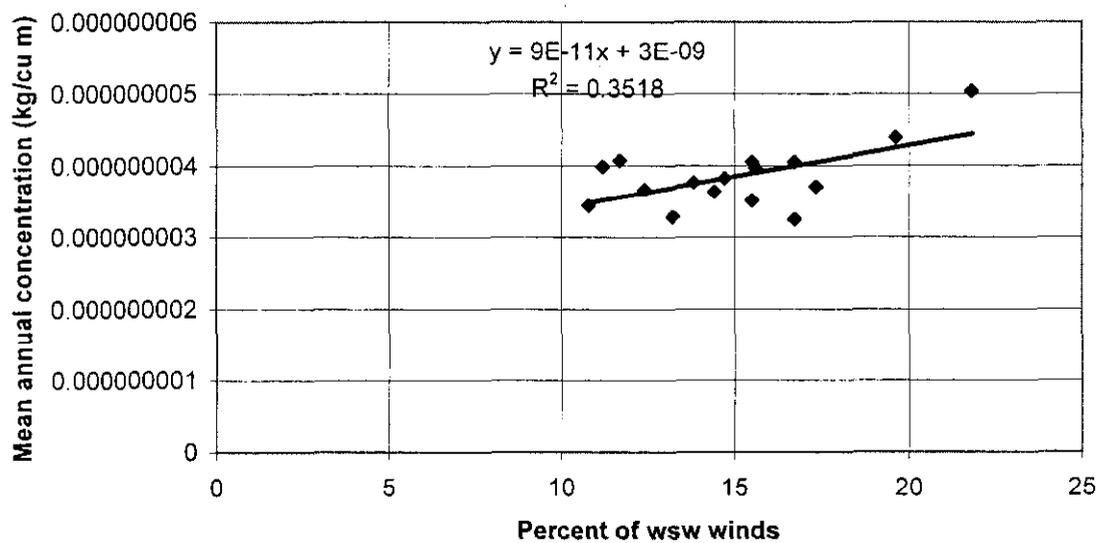


FIGURE 44 Short stack: winter day mean concentration and mean wind speed



**FIGURE 45 Short stack: winter night mean concentration and mean wind speed**



**FIGURE 46 Tall stack: mean annual concentration and percentage of winds from wsw**

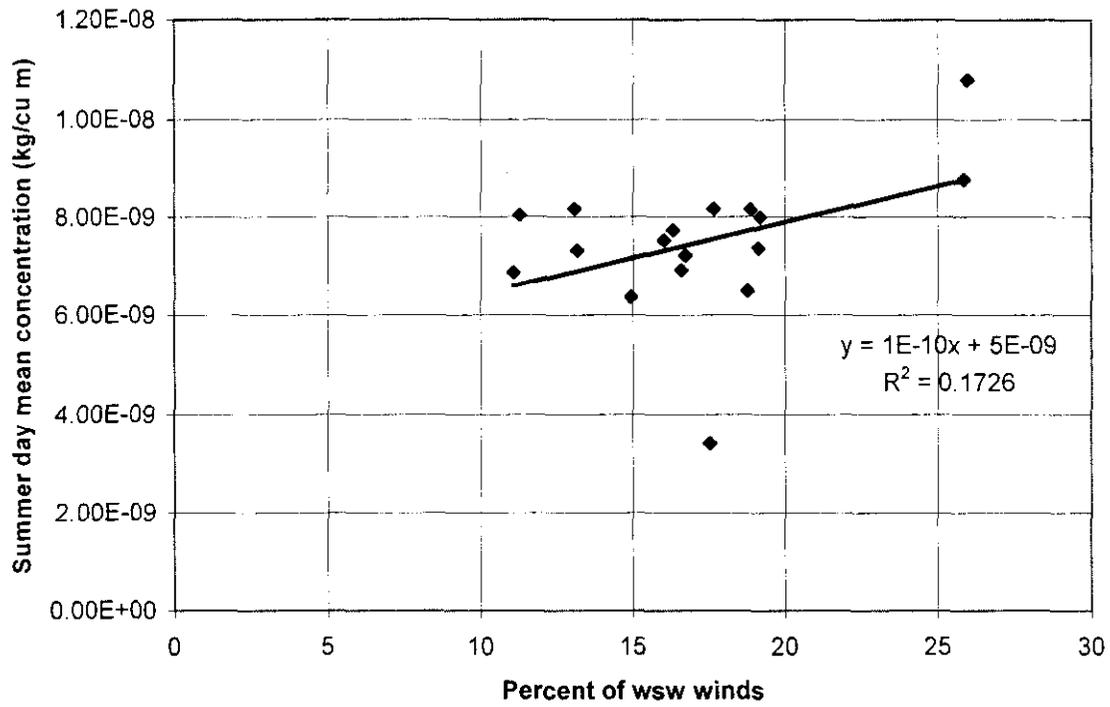


FIGURE 47 Tall stack: summer day mean concentration and percentage of winds from wsw

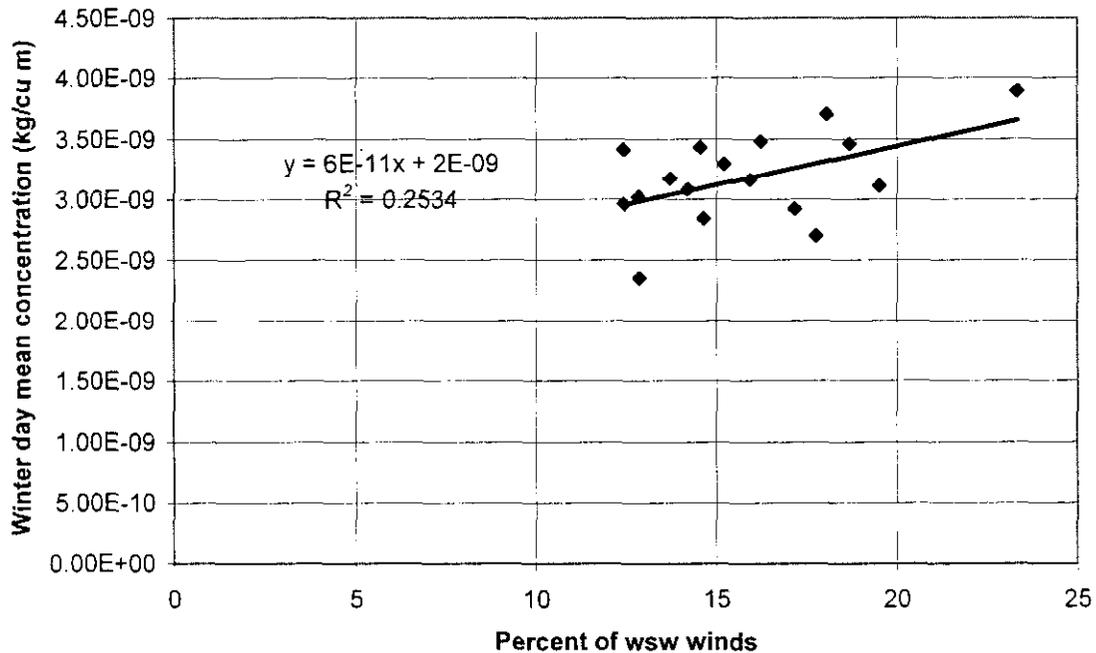
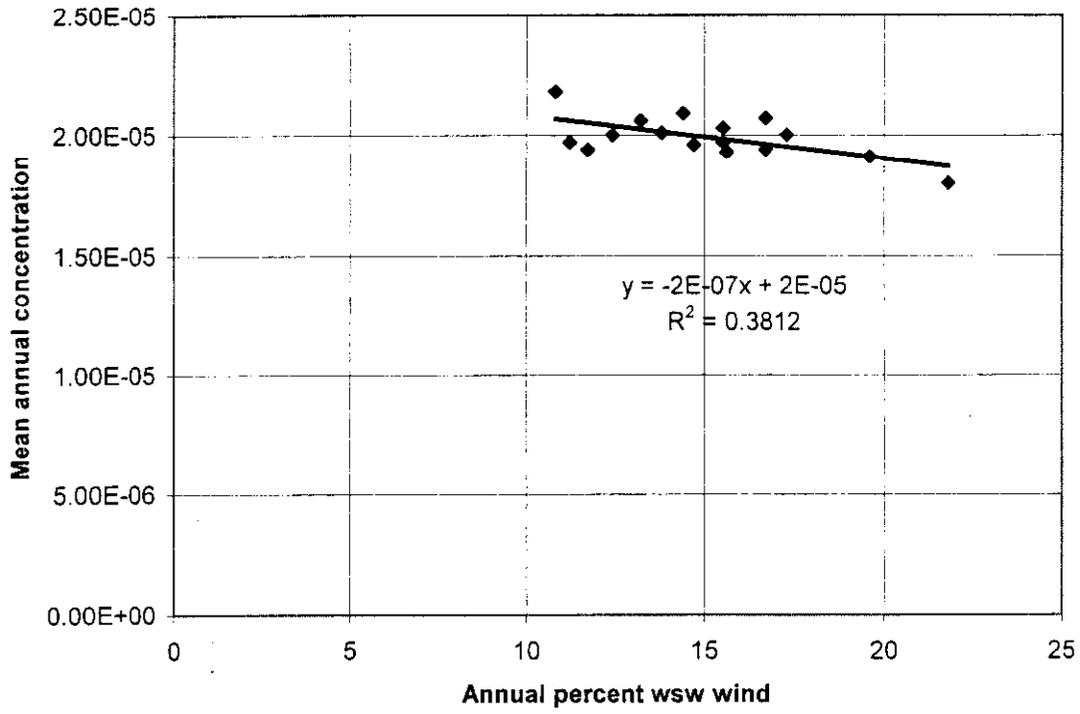
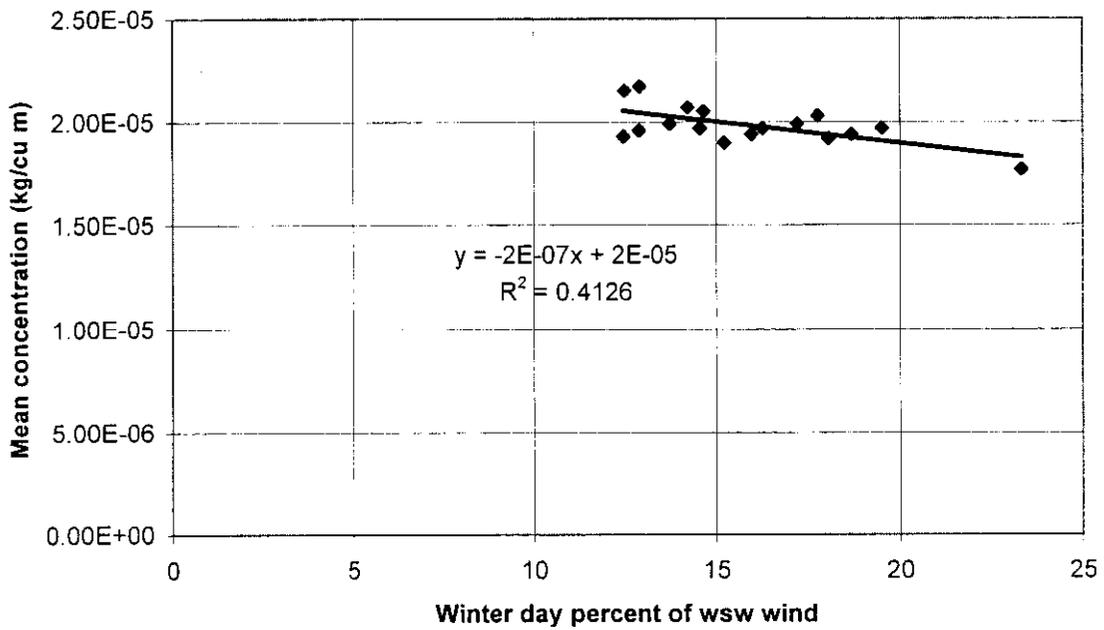


FIGURE 48 Tall stack: mean winter day concentrations and percentage of winds from wsw



**FIGURE 49** Short stack: mean annual concentration and percentage of winds from wsw



**FIGURE 50** Short stack: winter day mean concentration and percentage of winds from wsw

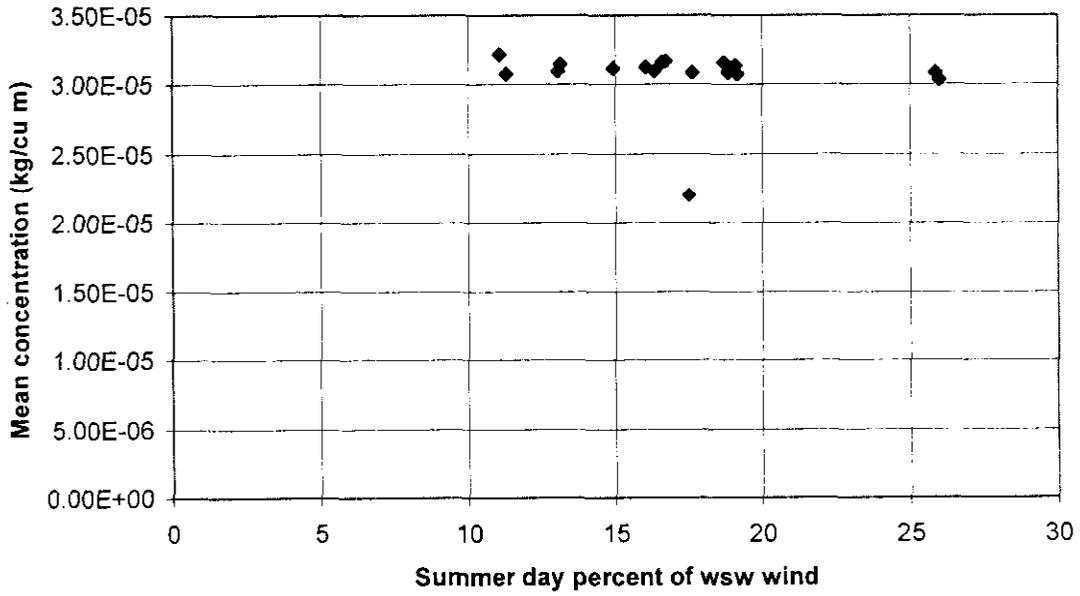


FIGURE 51 Short stack: summer day mean concentration and percentage of winds from wsw

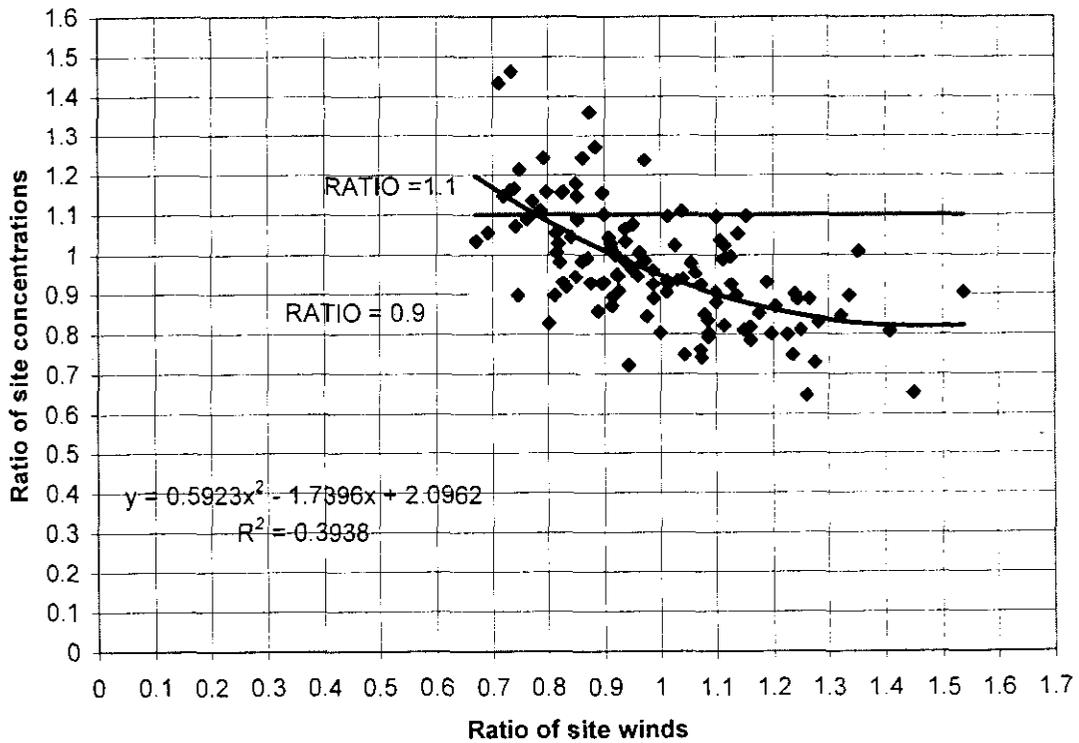
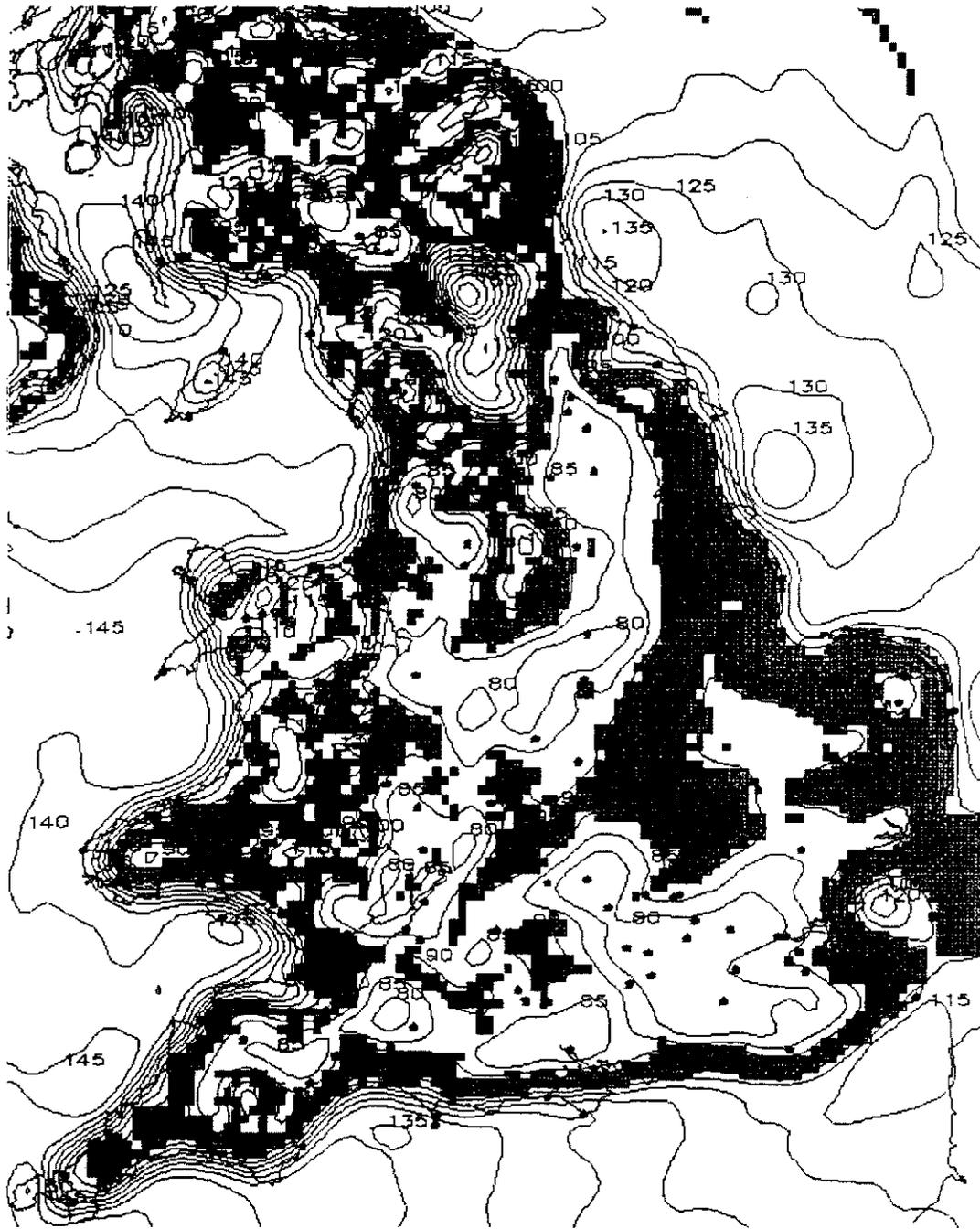
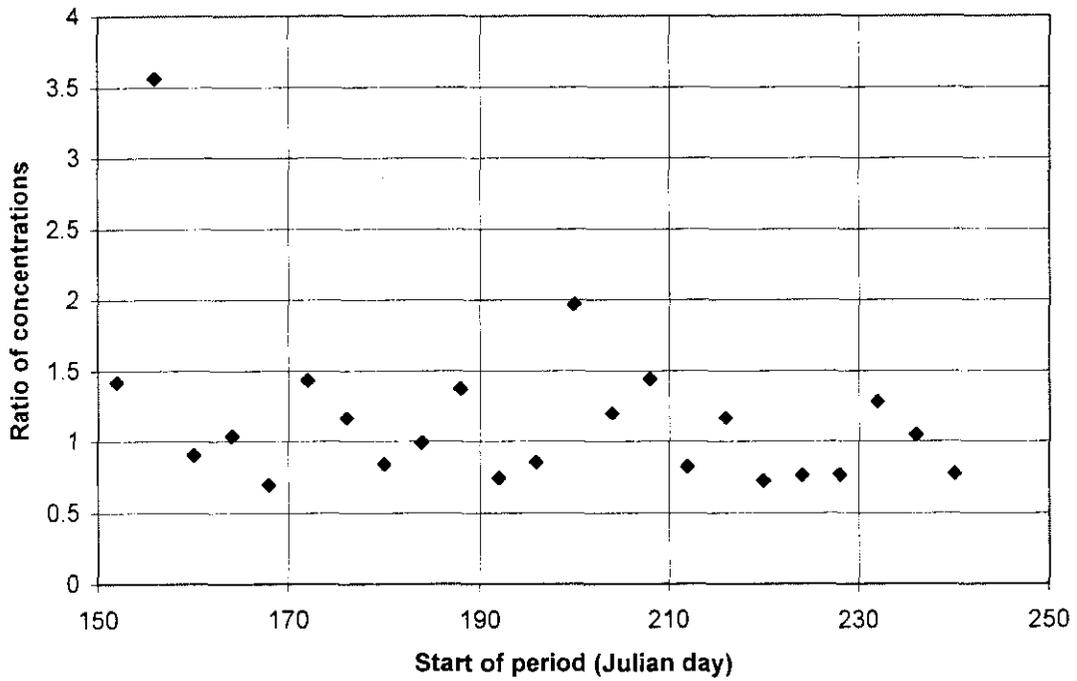


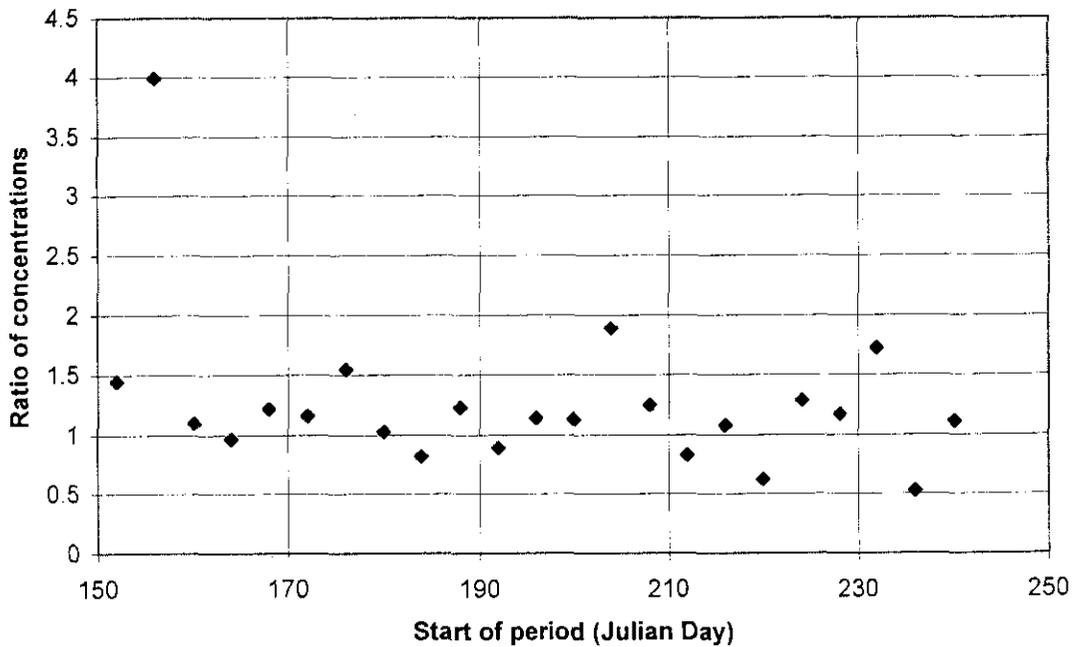
FIGURE 52 Tall stack: ratio of site mean annual concentrations and site mean annual wind speeds



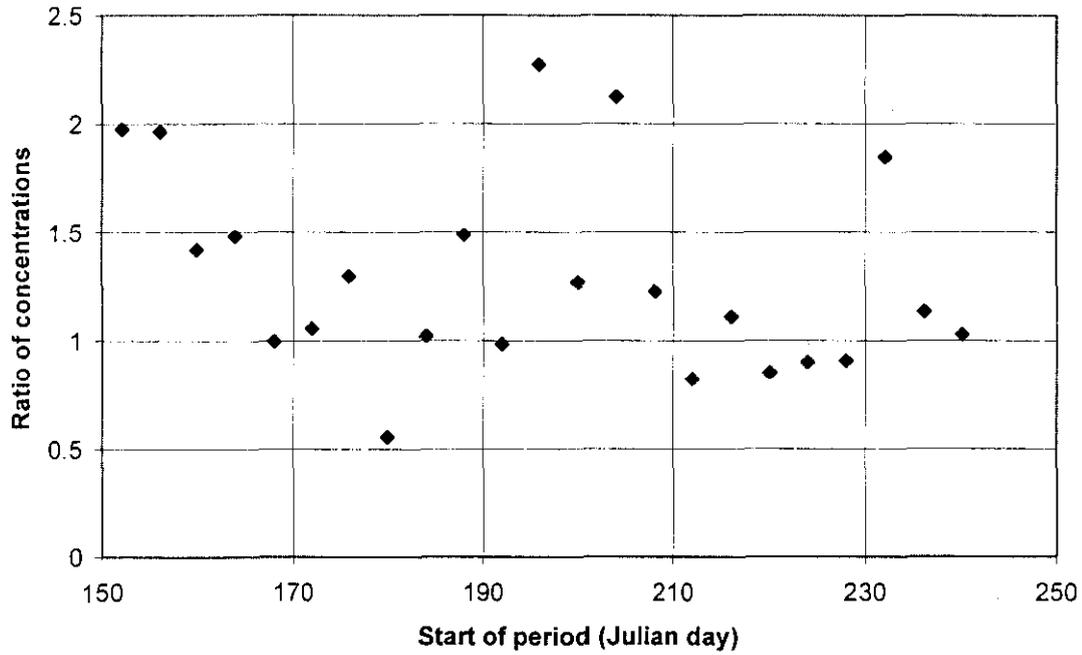
**FIGURE 53** Map which shows the ratio (expressed as a percentage) of the mean annual wind speeds relative to a site in Cambridgeshire with a mean annual wind speed of 10 kt. The grey area has wind speed within 1.1 and 0.9 of 10 kt. Anemometer sites are indicated by a symbol. The map is based on mean annual wind speeds for the period 1961–90 at 5 km resolution



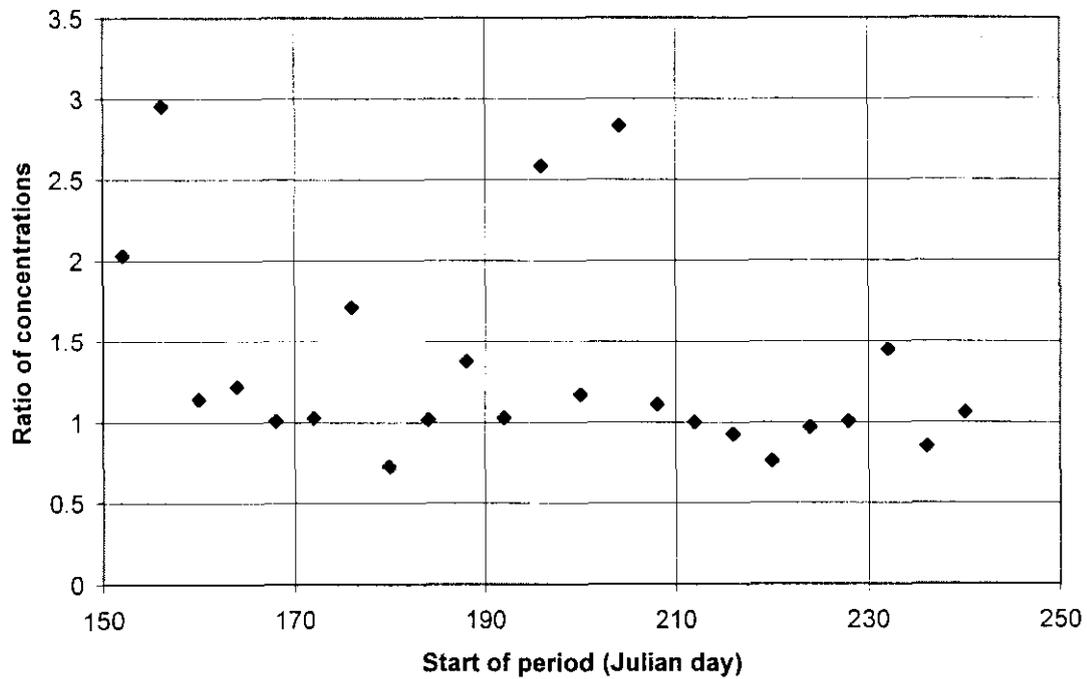
**FIGURE 54** Tall stack: ratio of maximum average concentrations for four-day periods: Heathrow/(Heathrow + Gatwick winds), June–August 1992



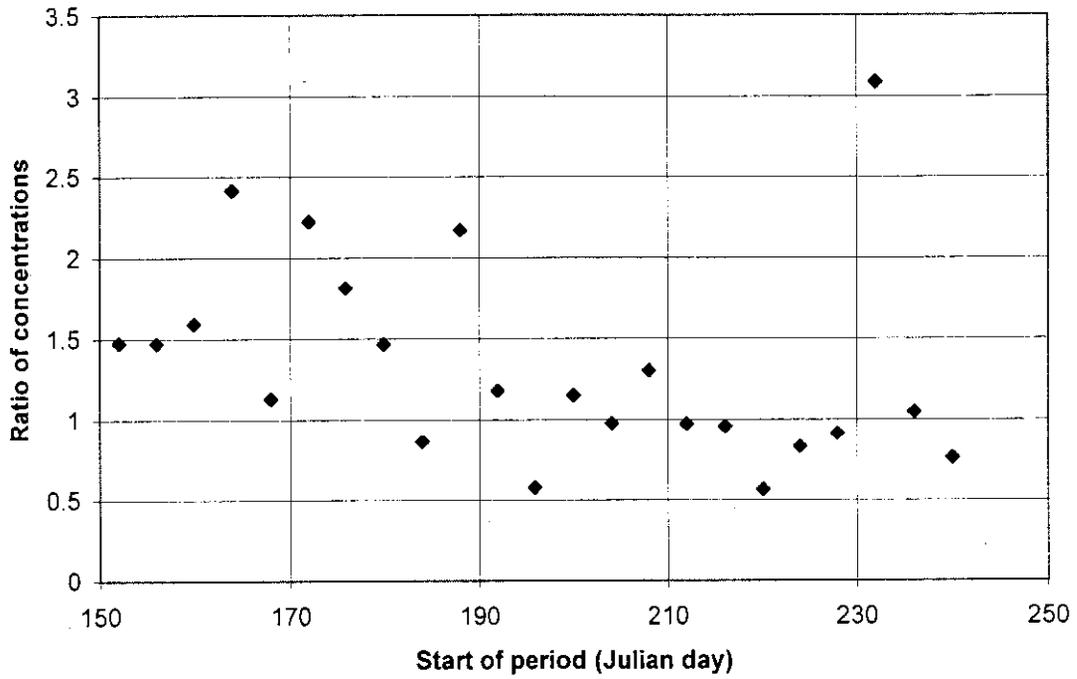
**FIGURE 55** Tall stack: ratio of maximum average concentrations for four-day periods: Heathrow/(Heathrow + Stansted winds), June–August 1992



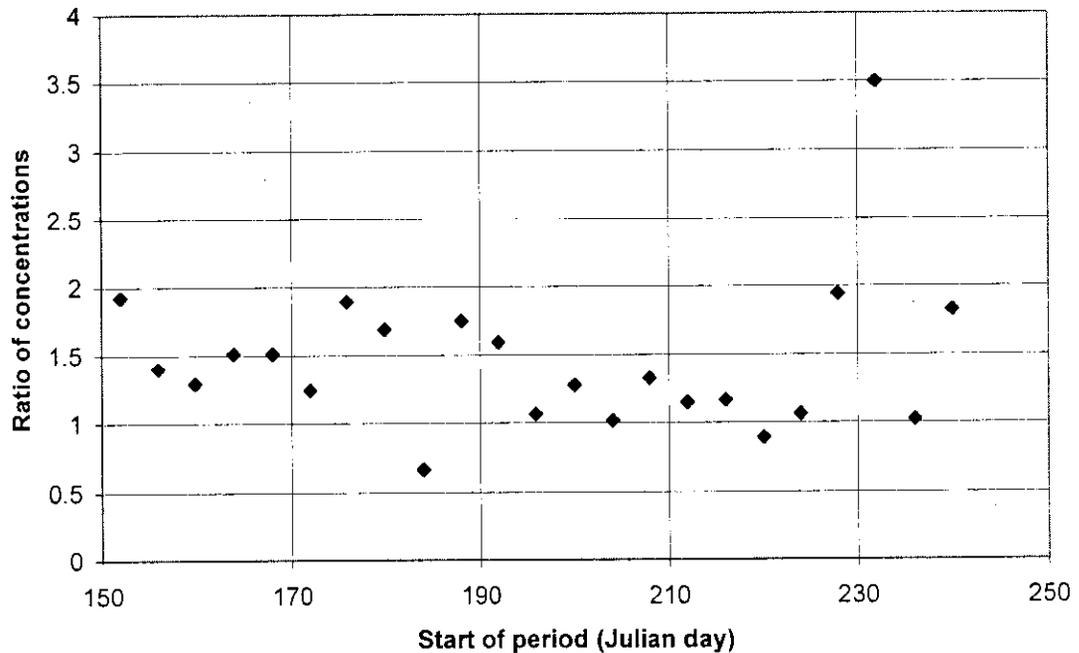
**FIGURE 56 Tall stack: ratio of 99th percentile concentrations for four-day periods: Heathrow/(Heathrow + Gatwick winds), June–August 1992**



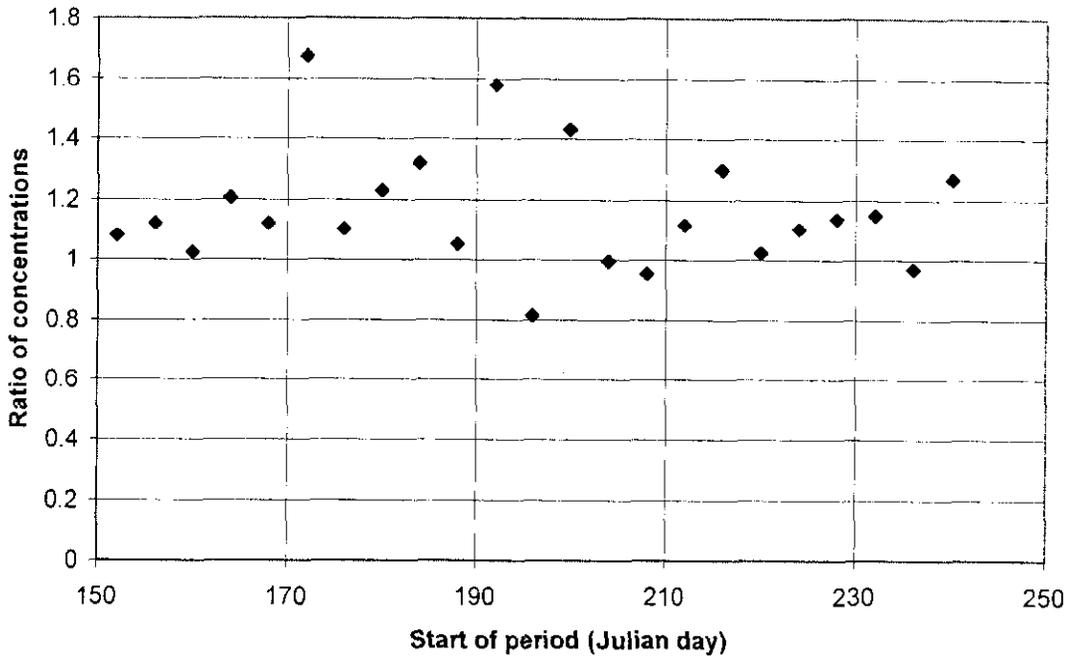
**FIGURE 57 Tall stack: ratio of 99th percentile concentrations for four-day periods: Heathrow/(Heathrow + Stansted winds), June–August 1992**



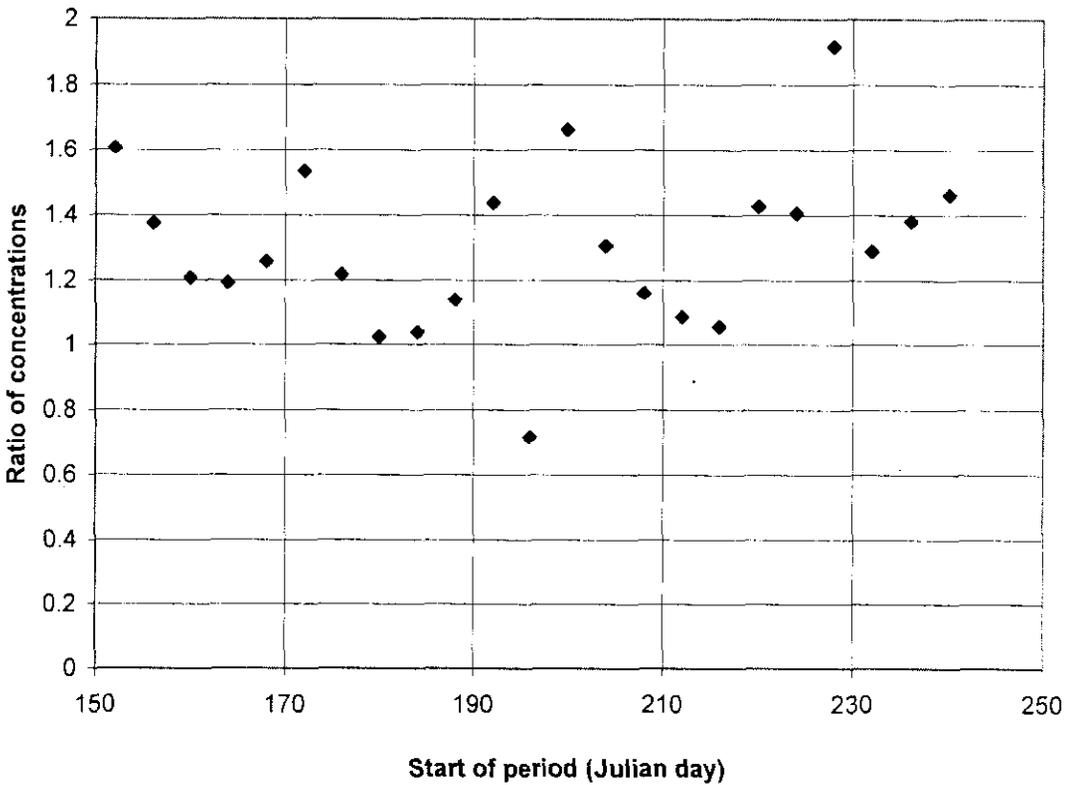
**FIGURE 58** Short stack: ratio of maximum average concentrations for four-day periods: Heathrow/(Heathrow + Gatwick winds), June–August 1992



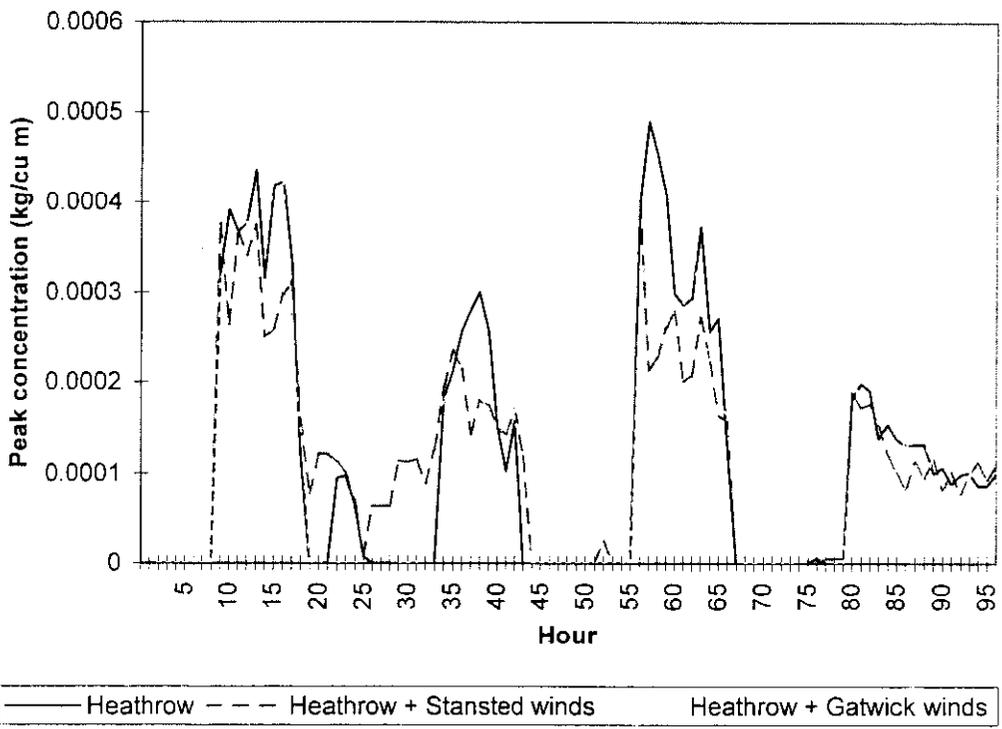
**FIGURE 59** Short stack: ratio of maximum average concentrations for four-day periods: Heathrow/(Heathrow + Stansted winds), June–August 1992



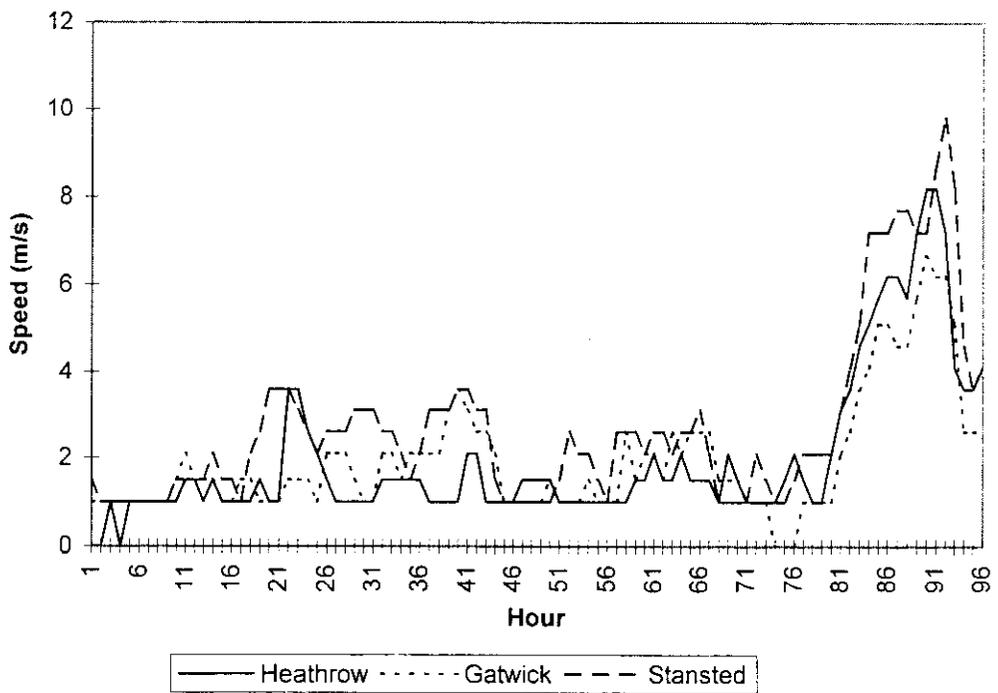
**FIGURE 60** Short stack: ratio of 99th percentile concentrations for four-day periods: Heathrow/(Heathrow + Gatwick winds), June–August 1992



**FIGURE 61** Short stack: ratio of 99th percentile concentrations for four-day periods: Heathrow/(Heathrow + Stansted winds), June–August 1992



**FIGURE 62 Short stack: peak hourly concentrations for 20–24 August 1992, for H, HG and HS**



**FIGURE 63 Hourly wind speed data for Heathrow, Gatwick and Stansted for 20–24 August 1992**