Exposure of Buildings to Pollutants in Urban Areas – A Review of the Contributions from Different Sources.

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SUMMARY

The paper describes the characteristics of different types of pollutant sources in the way that they are experienced in a fixed locality in an urban area. The locality in this sense can also be a building or part of a building (a ventilation inlet for example). The most important parameter is the distance of the polluting source and therefore the characteristic features of sources at different distances are discussed. The relationship between 'local' sources and 'background' levels of pollutants, their contributions to the total local pollution levels and the vertical and lateral gradient of pollution are considered. The discussion is illustrated by examples from measurements of dispersing plumes and of urban pollution levels experienced during a specific investigation in a large urban area.

Pollution levels can show large fluctuations, which increase with reducing time scales, and significant spatial variation over short distances. Measured pollution levels on four sites in a large urban area, the West Midlands, showed these characteristics for averaging times down to one minute and spatial separations of 500m. Data correlations between the sites were generally poor.

The paper has been prepared as part of the POLIS project in the EC JOULE 95 programme.

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1. INTRODUCTION

The high density of human activities in urban areas leads to a related high density of emitted air pollutants. As a result, urban areas tend to be amongst both the major sources of and sufferers from pollutants. Both pollutant sources and their effects are multifarious. Pollutants carried by the wind disperse to cover steadily increasing areas and those from different sources overlap and combine to generate the overall level of exposure that is experienced at particular sites.

From the point of view of the recipient, whether human or inanimate, the individual sources that form this total exposure may not be readily distinguishable. For example, a given level of exposure may come from a relatively small polluting source close at hand or a large source at a much greater distance. Similarly, the contribution of individual sources to the total cannot be readily distinguished at the point of reception unless they have markedly different characteristics.

This distinction is of more than academic interest. There is a natural and practical desire to avoid the effects of air pollution where possible. From a local point of view there may be no effective possibility of avoiding large polluting sources at long distances, which may pervade the whole urban area. However, there are greater possibilities for avoiding and controlling local sources so that their effects can be diminished by planning and regulation. This has been long recognised and the collection of urban emission inventories and their use in modelling pollution levels in urban areas became common practice as soon as it was a practicable activity (see for example, Benarie(1980)). Similarly, it is normal for static polluting discharges from combustion plant and industrial processes to be regulated by way of both emission controls and minimum heights of discharge stacks. In more recent years there has been an additional growing control over mobile emission sources (Schwela and Zali(1999)) .

Apart from the desire for pollution control in a public sense, there is also a more individual element of interest, for example in the choice of preferred sites for buildings or of the characteristics of buildings designed to suit particular sites. A particular example is the choice of ventilation systems and the placement of ventilation inlets and exhausts in order to minimise internal contamination problems. Dealing with such matters raises queries about the nature of the exposure to pollutants on specific sites and how it may vary from one site to another, over the area of the site or with the passage of time. Similarly, it may be useful to know whether pollutants are mainly due to local sources or otherwise. A further question may be the degree to which pollution levels on a particular site can be predicted from data collected elsewhere within the urban area.

It is difficult to deal with problems of this sort without some understanding of the character of discharged pollutants from different sources, especially those at varying distances, and the way in which their dispersion contributes to the overall pollution levels at a particular site. This is, of course, the usual subject of numerical dispersion studies of urban pollution. However, such studies do not cover all urban areas and it is unusual to find them using small resolution or short time scales. The smallest unit of area likely to be found in such a study is a kilometre square and the shortest time scale about an hour. At these scales vertical and lateral gradients in the pollutant concentration are likely to be small and many models do not, in any case, consider such matters . However, individual interests are often on significantly smaller scales than this. The site of a single building, for example, may occupy scales of only

100m or less. Within these smaller scales there can be quite large variations in pollution levels in space and time which are significant from this smaller scale point of view.

A major factor in the dispersion of pollutants in urban areas is the severe topography due to the large number of surface obstacles, mainly buildings but including a variety of other structures. The effect of the urban topography on wind effects is well known and much discussed (see, for example Cook(1985, 1990)), but its effects on the dispersion of pollutants at short ranges within the 'urban canopy' is less well understood. The requirements for simple short range dispersion models in urban areas have recently been reviewed by Hall et al(1996b) who discuss these problems in more detail.

The relationship between pollution levels at these different scales is the subject of discussion in the present paper. It is dealt with in a generic way, rather than with reference to specific pollutants or pollution problems and illustrated with examples from dispersion studies, both at full and model scales, and with pollution monitoring data from urban areas. One of the most important features that distinguishes the character of different pollution sources is their distance from the point of interest, so that in the discussion that follows the characteristics of pollution sources are mainly treated in terms of increasing distance.

2. DISPERSION OVER DIFFERENT SCALES IN URBAN AREAS

2.1. The Definition of Scales and Spatial Variability.

The term 'scale' of air pollutants can apply to both space and time. Both are important for various reasons and they are connected by way of the mean windspeed, which sweeps pollutants over a specific area in a given time while dispersing them. In his thorough and very interesting monograph on 'The Design of Air Quality Monitoring Networks', Munn(1981) covers a number of aspects of urban pollution that are relevant to the present discussion. In considering time and space variability, he defines some characteristic scales of spatial air pollution patterns, which in order of increasing size are:

microscale (0-100m)
neighbourhood scale (100-2000m)
urban scale (5-50km)
regional scale (100-1000km)
continental, hemispheric and global scales

The ranges are as defined by Munn and do not overlap. However , as the values are approximate this is not important. These are roughly the different scale orders that have been used here, as they correspond fairly well to the different types of dispersion patterns that occur. Only the first three scale orders are of direct interest as variables within the scale of urban areas. Pollution levels at the larger two scales would show no significant variation over the scale of an urban area and would class as contributors to the 'background level' pollutants in the area. Quite what should be classed as 'background' levels of pollution is considered later in the paper.

In a similar way, Munn defined a number of characteristic time scales associated with pollutants:

minute to minute variations
the daily (diurnal) cycle
large scale weather fluctuations (3-5 days)
weekly emission cycles
annual emission and weather cycles

It can be seen that these are associated either with natural meteorological cycles or with patterns of human activity. For the shorter ranges mainly of interest here, it is useful to subdivide the shortest time scale into two further divisions related to the stochastic (that is, the unsteady) nature of dispersing pollutant plumes:

times below which the fluctuating characteristics of dispersing plumes are apparent (typically seconds)

times beyond which the time-averaged concentrations in dispersing plumes are stable (typically minutes)

The time scales associated with this subdivision are a little arbitrary as the time scales for stable time-averaged concentrations do not have finite limits and are also affected by large scale wind disturbances, of the sort readily generated by windflows around buildings in urban areas.

It was noted earlier that the spatial and time scales are related to some extent by the windspeed. Thus, taking typical UK windspeeds around the mean, say 3-5m s^{-1} , the microscale and shorter neighbourhood scales are associated with time scales of seconds, the longer neighbourhood scales and lower urban scales with time scales of minutes and the upper urban scales and regional scales with time scales of hours. The continental and larger scales correspond to time scales approaching days and beyond.

It is the combination of the multiplicity of discharged polluting sources from this range of distances in the generally upwind direction that produces (simply by the summing of instantaneous pollutant concentrations) the overall pollution level that is experienced at the point of interest. In principal, the contributions of these sources to the overall level are not distinguishable and one of the major reasons for dispersion modelling is as a means of making this distinction. However, there are differences in the character of the contribution from sources at different distances, both in their spatial and temporal characteristics, that help to identify them and their contribution to the total. The ensuing discussion attempts to characterise these differences and the ways in which they affect the combined pollution levels experienced at the point of interest.

2.2. Dispersion at Short (Microscale) Ranges.

The definition of ‘short ranges’ is a little arbitrary, but implies here sources which are mostly within direct line of site of the point of interest or where dispersing plume widths are relatively small compared with the scale of the surface obstacles. The practical range may be anywhere from 10m to 1km, and in exceptional cases further. Thus this may embrace both the

microscale and neighbourhood scales defined by Munn. For low level sources in urban areas the limiting distances are usually of a few hundred metres and are thus closer to Munn's microscales.

The critical characteristics of dispersing plumes within this scale range are their high pollutant concentrations, small footprint, rapidly fluctuating intensities and (especially within urban areas) meandering qualities. The majority of polluting discharges are from 'point' sources, that is their cross section at discharge is small compared with the plume cross section even at short distances. This applies, for example, to most combustion and process plant discharges, vehicle exhausts and many ventilation discharges. In these cases undisturbed discharge plumes are highly concentrated, most of the pollutant material is contained within a subtended angle from the source of about 10°. Thus within the small area of the dispersing plume there are high concentrations of pollutant, with little pollutant material elsewhere. Also, because of the stochastic (unsteady) nature of dispersion, there will be large variations of concentration within the plume itself. Figure 1 (taken from Hall and Kukadia(1994)) is a visualised dispersing plume which shows clearly the intermittent nature of the concentrations locally within the plume. Because of the stochastic properties of dispersing plumes, at distances within a few hundred metres it is possible for small regions of undiluted source material to exist and this has been observed in field experiments by Jones(1983).

Besides the internal variability of pollutant concentration in the plume, the wind environment near the ground in urban areas usually shows a high degree of variability in speed and direction due to the aerodynamic disturbances from buildings and other large structures. This introduces an additional variability in the plume path, usually described as plume 'meandering'. Thus the overall characteristic of exposure to a dispersing pollutant at short ranges is usually of relatively infrequent, highly intermittent exposure over short periods (of the order of seconds) to relatively high pollutant concentrations. The importance of rapid fluctuations in pollutant levels in a number of applications has recently been discussed by Jones(1996).

In urban areas one strongly modifying factor to this description is the ability of buildings and other large structures to generate rapid dispersion of discharged pollutants over large areas in the aerodynamic wake regions behind their downstream faces. This generally results in a much larger area of exposure to the pollutants, though at lower concentrations than with the slender plume, and in a more persistent and time-continuous form.

Figure 2 shows an illustration (Taken from Hall and Kukadia(1994)) of these two types of exposure to a dispersing plume at short ranges. It shows measurements made in the field by Helen Higson of the Environmental Technology Centre, UMIST, of a pollutant plume approaching and dispersing around a rectangular building in otherwise smooth terrain. The plots are of pollutant concentration against time and show two cases, in the undisturbed plume upwind of the building (case a) and in the region of rapid dispersion in the wake region behind the building (case b). On both plots the mean concentration is shown as a broken line. The traces are typical of the two types of dispersion. That in the undisturbed plume shows large variations in concentration , with fluctuations well in excess of the mean, over periods of seconds, and a high degree of intermittency (that is, there are significant periods when no pollutant is present in the plume). The concentration/time trace downwind of the building shows the continuous presence of pollutant with relatively low levels of fluctuation, so that levels of concentration remain close to the mean. If the plume were dispersing in an urban

area, the concentration trace upwind of the building would show additional intermittency due to meandering of the plume and thus longer periods without the presence of any pollutant.

Exposure to pollutants at short ranges in urban areas is a combination of these two types of dispersion pattern, depending upon the siting of the discharge and the presence of buildings and other surface structures. The form of the exposure need not be one type or the other , it is also possible for both regimes to occur together, so that the exposure is the sum of the two traces in Figure 2. Figure 3 shows a sketch of a situation in which this will occur, with a polluting discharge on the downwind side of a building. Here, over the longer term the discharge is dispersed in the building wake region, as in Figure 2b. However, since the point of discharge is also in the building wake region, in the shorter term there is an additional exposure to the highly concentrated meandering plume in the disturbed flow in the building wake, as in Figure 2a.

A practical example of this is shown in Figure 4 (taken from Hall et al(1996a)), which shows small scale wind tunnel measurements of concentration/time traces at the ground behind a building of similar shape to that of Figure 2, for a pollutant source just behind the building at different heights ranging from ground level to 1.5 building heights. With the source on the ground, the mean wind carried the dispersing plume away from the point of measurement, so that only the longer term concentrations in the building wake, as in Figure 2b, were observed. However, for the next two pollutant source heights the discharge was within the wake region and the sampling station recorded both the longer term concentrations in the recirculation regions together with shorter term intermittent high concentrations from occasional exposure to the meandering plume. The final source height, at 1.5 building heights, discharged pollutant above the wake region, but part of the plume dispersed downwards and was entrained into the building wake further downwind. The sampling point was again then exposed to the two types of dispersion pattern, but concentrations were lower than before as only part of the dispersing plume was entrained into the wake. In urban areas, where the occupational density of buildings and other structures is high, dispersion patterns like those in Figure 4 are likely to be the most frequently occurring at short ranges.

Polluting sources at short ranges generate high levels of spatial as well as temporal variability in urban areas. The disturbed windflows that are a feature of urban areas generate a spatial variability that is not only high but which is also sensitive to source position and to the meteorological parameters, especially wind direction. There can, for example, be very large variations in pollutant concentrations across the corners of a street intersection or between the windward and lee faces of a building. It is not proposed to discuss this complex subject in detail here, but a few examples of small scale plume behaviour at short distances are given which show the effects clearly enough. Figure 5, taken from Dabbert et al (1973), shows an over-simplified representation of the flow pattern in the space between buildings in an urban area, frequently described as a ‘street canyon’. Figure 6 , from Oke(1987), shows some mildly misleading representative dispersion patterns in urban areas covering a variety of source positions and shows the complex plume paths that can occur. Diagrams like those in Figures 5 and 6 usually imply a wind square on to the layout of buildings and streets and fail to take into account the additional complexities introduced by the more commonly occurring wind directions, which are skewed diagonally across the street array. Figure 7, from Hoydysh and Dabbert(1994), shows a more realistic example of the large variations in mean concentration that can occur at a street intersection for a fixed wind direction skewed across the street array (the measurements were made using a small scale wind tunnel model).

2.3. Dispersion at Neighbourhood Scales (100-2000m).

Within the greater distances of neighbourhood scales, the high levels of spatial and temporal variability that mark out microscale dispersion patterns reduce. Though spatial and temporal variability in concentration remain, the associated time and distance scales increase. Apart from distance itself, the most important factor influencing this change remains the surface topography, mainly the buildings and other surface obstacles. At these greater ranges, however, it is the size, layout and packing density of the structures in urban areas that are the most important features, rather than the shapes of individual structures and their immediate surroundings, as is more the case with microscale dispersion patterns.

As a rule of thumb, once a source of pollutant is out of line-of-sight in an urban area, the effects of building wakes on dispersion become more important, so dispersion patterns become more stable and the short term variations in concentration should pass from a state like that of Figure 2a to one more resembling that of Figure 2b. With increasing distance the diffusing effects of larger numbers of buildings come into play and the variability further reduces. There remain additional complex types of behaviour related to the surface topography. For example, the tendency of pollutants to be channelled along clear paths in the surface topography due to street patterns, which causes higher concentrations in this region.

The spread of pollutants at neighbourhood scales is not presently a well researched subject, though this is a rapidly growing interest (Hall et al's(1996b) review discusses most of the existing literature). It is difficult, therefore, to provide a clear description of pollutant dispersion at these distances. As noted above, it is the size, layout and packing density of the buildings that most affect the spread of pollutants. The most recent research suggests that, of the characteristics of the urban form affecting the spread of pollutants, it is the mean height and across-wind widths of the surface structures which has the greatest effect. The typical characteristic of the spread of pollutants at neighbourhood scale is a rapid vertical mixing over (and a little above) the heights of the surface structures in distances covering 3-4 rows of buildings in the direction of the wind. Beyond this distance there is a slower rate of vertical spread to greater heights. Lateral spreading is fairly rapid over the individual building widths and further lateral spreading at greater distances depends upon the relationship between building widths and spacing.

It is within the neighbourhood scales and microscales that significant vertical gradients of pollutants can occur. This is a matter of practical interest, for example for human exposure and for the placement of ventilation intakes. As a broad generalisation it might be considered that pollutant sources at or close to the ground would produce falling levels of pollutant concentration with increasing height and that pollutant sources at or above the building heights would produce rising pollutant concentrations with increasing height. In urban areas the dominant near-ground pollutant source is vehicular traffic. A recent emission inventory for the UK West Midlands area has suggested that vehicle emissions are now the major urban polluters (Anon(1996)); similar estimates have been made for Copenhagen and Milan(Vignatti et al(1996)). The dominant pollutant sources at or above building height are mainly discharges from combustion plant and industrial process, for most of which activities there are regulatory requirements in the UK that discharges should be above their immediate surroundings. However, there are in addition a variety of other pollutant discharges at

intermediate heights, for example ventilation exhausts (which are often associated with odour problems), standby generators and discharges from some types of gas-fired heating plant.

This broad generalisation for vertical gradients of contamination is of limited reliability. The plume paths sketched in Figure 6 indicate that at the shorter scales there may be substantial short term local variations in the vertical pollutant gradient for sources at any height from changes in the dispersion patterns due to local aerodynamic effects. The longer term mean of the vertical gradient of pollutants can also vary. Figure 8 shows measurements of the vertical variation of pollutant from sources at the ground in a small scale simulation of an urban area in a wind tunnel, using arrays of cubes set in rows. Measurements are shown for the surface obstacles occupying 16% and 69% of the ground surface area (the 'Area Density'), typical values respectively for a suburban housing estate and the more densely packed central region of an urban area. The pollutant profiles are at distances covering one, three and about ten rows of the surface obstacles, which is a more important criterion than the absolute distance. For a typical urban area with buildings 10-20m high, the equivalent range of distances was from 100m to 2km. The height of the obstacles is marked as a 'building height' on the plots, below which the plot is shaded. For the greatest distance both plots show quite uniform gradients of pollutant to heights well above the obstacles. However, at the shorter distances of a few rows of the obstacles there are sharper gradients, both positive and negative. The measurements show positive gradients near the ground at the shortest distances (behind a single row of obstacles) for both area densities. However, with increasing distances covering additional rows of the obstacles the gradients become more uniform at the lower area density but pass from positive to negative at the higher area density. In all the cases of distances up to a few rows the gradient near the top of the obstacles was negative, so that there was a distinct reduction in the level of pollutant at the tops of the obstacles. The implication is that pollutant levels from nearby ground-based sources may well be significantly lower at roof level than lower down, but that below roof level pollutant levels can vary in complex ways with no certainty as to the vertical gradient of pollutant. It can also be seen in Figure 8 that, at a given distance from the source, pollutant concentrations are significantly greater for the higher density of obstacle packing than for the lower density.

There seem to be few field measurements of the vertical gradient of pollutants in urban areas. Figure 9 shows some early measurements by Georgii et al(1967) of carbon monoxide (CO) on either side of a street. Since vehicular traffic is the major source of CO, the measurements are largely for a distributed, ground-based source. In this case the gradient is of reducing concentration with increasing height, but it is interesting that measurements either side of the street are markedly different, the windward side having the lower values. Figure 10 (taken from QUARG(1993)) shows the results of a scan by a remote sensing device (a LIDAR) of the contours of NO_2 in a London street with dense traffic. The concentrations fall with increasing height above the ground, but show another maximum above building level. It was remarked in this context that the higher maximum might be due to further oxidation of NO to NO_2 above the buildings, where more ozone was present. This argument seems a little tenuous for such short time and distance scales, but the higher maximum could equally well be due to a high level discharge from a local combustion plant or some feature of the local dispersion pattern.

2.4. Dispersion at Urban Scales (5-50km).

Pollutant sources at these distances and beyond disperse to heights well above the heights of the surface structures and spread over relatively large widths. At 5km distance the bulk of the pollutant from a single source is contained within a height of about 250m and a width of about 1km. At 50 km distance the respective heights and widths are about 600m and 8km. Pollutants are then starting to mix uniformly within the depth of the surface boundary layer. Also, the large numbers of pollutant sources likely to be contained in the upwind fetch at these scales, which contribute to the total pollution level at a point by addition, produce a more diffuse and slowly changing pollutant level. Thus there are negligible vertical and lateral concentration gradients over all but the very largest surface structures. This is also the regime for which pollutant residence times in the atmosphere are sufficient for chemical processes to occur, for example the oxidation of nitrogen monoxide, NO, to nitrogen dioxide, NO_2, and the generation of photochemical smog.

Most urban modelling studies are carried out at these and greater scales, using mapped inventories of emission data from various pollutant sources and suitable meteorological data. Traditionally these have been concerned with predicting pollutant levels over relatively long averaging periods, from a day to a year. However, with the recent recommendations of shorter term exposure limits for human exposure to sulphur and nitrogen oxides (EPAQS (1995), EEC(1985)) there is a growing interest in making shorter term predictions. Two examples of the results of modelling studies are shown here. The first, due to Ott(1977), in Figure 11, is a hypothetical example of the pollutant concentration pattern to be expected from vehicular traffic occupying a grid of streets. It shows the higher levels of pollutants at the junctions and the rapid fall-off of pollutant levels away from the road that appear to occur in practice. This can be compared with the measurements of pollutant concentration at a road junction shown in Figure 7 from a small scale model experiment, which also show the high concentrations at the junction. The second is due to Timmis and Walker(1989), in Figure 12, and shows contours of calculated estimates of winter mean sulphur dioxide levels in Kirkaldy in Scotland.

2.5. Dispersion at Regional and Continental Scales (100km +).

Pollutant sources at these distances uniformly pervade the surface boundary layer, and thus to heights usually well above those of the surface structures, and show only small variations over large areas and long times. At the same time, the pollutant level at a point is usually composed of the sum of the contributions from a very large number of individual sources. At the longer distances of these regimes even diurnal variations in pollutant discharges are smoothed out and pollutant levels mainly vary with changes in the weather pattern or long term patterns of use. The ‘upwind’ pollutants may have followed complex wind trajectories generated by the weather pattern. These are also the scales at which longer term atmospheric chemical processes occur, such as the further oxidation of nitrogen and sulphur oxides to nitrate and sulphate.

Pollutants at these distances thus constitute the true ‘background’ concentration levels of urban areas in that they pervade the whole area at a uniform level which changes only slowly. They cannot be controlled or avoided within the scales of an urban area. Otts’ diagram in

Figure 11 includes a base level of background pollutant concentration to which the local sources additionally contribute.

2.6. The Overall Pollutant Concentration Level Due to the Contribution of Sources at Varying Scales and 'Background' Concentrations.

It was remarked earlier in this paper that it is the sum of the pollutant concentrations from the multiplicity of pollutant sources at the whole range of upwind distances that produces the overall pollutant concentration level at a point of interest. From the descriptions of the temporal and spatial character of the pollutant levels from sources in the different distance regimes it will be appreciated how the overall pollutant level is built up from components with a variety of characteristics. Figure 13 shows a hypothetical example of this, with the components from the different distance scales summing to produce the total pollutant level at some point in an urban area. The level of temporal fluctuation and its frequency increases as the scales of the pollutant source distances increase. Thus the high frequency component of the overall pollutant level is due to the microscale and neighbourhood scale components and the stable long term base level of the pollutant concentration is due to the urban, regional and continental scale components. The spatial variability can be expected to follow the same sort of pattern, with the microscale and neighbourhood scales sources producing the greatest spatial variability and the urban, regional and continental scales the lowest. It will also be appreciated that it is not readily possible to determine the precise contributions of pollutant sources at the different scales to the total pollutant concentration level except, within limits, by their different frequencies of fluctuation.

The form of the overall pollutant concentration curve with time in an urban area will depend upon the relative contribution from the different distance regimes. For example, in the UK if there is an anticyclonic weather pattern with light easterly winds during a holiday period, then the long range contribution of pollutant sources from Europe will be high and the urban and smaller scale contributions will be low. Thus the overall curve will show low relative levels of short term fluctuation and low spatial variation. Alternatively, if there are westerly winds carrying relatively uncontaminated air from the Atlantic during a busy working day, the long range contributions will be low but the urban and smaller scale contributions will be relatively high. Thus the overall curve will show a higher level of short term fluctuation over a relatively small 'background' concentration.

The question of what should be considered as 'background' pollution is not formally defined. It tends to be regarded as a nearly constant, all pervading level of the pollutant over the area which changes only slowly with time. As noted earlier, on this basis it is pollutants dispersing over regional and continental scales that may be regarded the true 'background' level of pollutant. However, 'background' is also used to describe the longer term average pollutant levels, irrespective of their source. This is a common procedure when, for example, dealing with the additional contribution of a new local source of pollutant. However, in this case it will be appreciated that there will shorter term excursions in the pollutant level locally which are well above the 'background'. The definition of a 'background' level thus depends to some extent on the purpose to which it is put. From the point of view of, say a single building, any pollutant level which is largely unvarying across the scale of the building might be regarded as a 'background' level of pollutant. This would imply spatial scales of the order of a few hundred metres, though the associated temporal scales would be typically some tens of seconds. If, as an alternative, a 'background' level was required that indicated the

average level of exposure of a building ventilation system over its air exchange rate, a temporal scale of between ten minutes and an hour would be more appropriate, with the implied urban and regional spatial scales.

3. Some Examples of Urban Pollutant Data.

3.1. Pollution Monitoring Sites in the West Midlands Area.

To provide an illustration of the characteristics of pollutant levels in urban areas we have used data from the UK National Network Sites in The West Midlands to investigate the degree to which pollution levels at a particular site are related to those at different sites within the same urban area. There are three sites normally operating in this large urban area, but for an additional period, recently, BRE carried out measurements of pollutant levels in the same area as part of a building ventilation study (Kukadia and Palmer(1996), Kukadia et al(1996)). The ventilation study incorporated both external and internal measurements of various pollutants at a site in the centre of Birmingham. This has in effect provided an additional monitoring site as well as a comparison of indoor/outdoor pollutant levels. The main interest here is in the external measurements. The original report on this study (Hall et al(1996c)) contains additional data to that shown here.

A map of the West Midlands area showing the National Network sites, the site of the building used for the ventilation study and of the meteorological site are shown in Figure 14.

The buildings used in the ventilation study (site B in Figure 14) were located in the central commercial district of Birmingham close to a busy eight-lane roadway (Great Charles Street). The external measurements were made outside the naturally ventilated building (referred to as the CB building) about 3m above the footway at the side of this main road. Of the three network sites (sites 1,2 and 3 in Figure 14), the closest to this building is the Birmingham Central site which is about 560m to the south-west. This site is located in a pedestrianised area (Centenary Square) 100m from a main road and 10m from a small car park. The other two network sites are located further away from the city centre. The Birmingham East site is about 5km ENE of the building and is sited within the playground of a junior/infant school in a residential area. Finally the third site, at Walsall, about 13.5km to the north of the city centre, is also a school site in a residential area, but is 200m west of the M6 motorway (carrying 70,000 vehicles per day) and 500m north of a smelting plant.

Pollutants monitored at the ventilation study site included SO_2, NO, NO_2 and CO, these are also monitored at the two Birmingham network sites. The Walsall site only monitors NO and NO_2 , so we have mainly looked at NO_2 as a common pollutant between the sites. Examples of the latest annual data (taken from AEA(1995)) are reproduced in Figure 15 for hourly measurements of NO_2 at the three sites. The annual mean levels are broadly similar at 46ppb (Birmingham Central), 38ppb(Birmingham East) and 61ppb (Walsall). However, inspection of the plots in Figure 15 shows that though there are some observable peaks in common (like that towards the end of December), the shorter term fluctuations show only limited similarities between the sites even on this basis of hourly averages.

Data at the CB building were available for the period 14 to 21 February 1996 and so this period was chosen for more detailed study. For the ventilation study the data were recorded with an averaging time of 5 minutes, however only 15 minute averages are available for the network sites and so 15 minute averages were calculated from the CB building data. Data for

shorter averaging times than 5 minutes is difficult to find; most pollution monitoring instruments need to average over a few minutes to smooth instrument noise from the signal at low levels of concentration. However, there were significant differences between even the 5 and 15 minute averaging times noted above. Figure 16 shows this difference for one example, for SO_2 measurements on 14th February, together with data for a 60 minute averaging time; this latter averaging time matches the hourly mean annual data shown in Figure 15. The data shows significant additional fluctuations with reducing averaging times, especially for 5 minute averaging time compared with 15. Shorter averaging times than 5 minutes would show much greater fluctuations.

Hourly wind speeds and directions were obtained from Birmingham University as part of the ventilation study. The University is located about 4km south-west of the city centre, as shown on the map in Figure 14.

The weather in Birmingham during the week of measurements began with a mobile anticyclone crossing the country on the Wednesday and Thursday (14th and 15th of February), resulting in fairly low windspeeds (1-5m s^{-1}) from the north-west over Birmingham. This period was followed by a return to a changeable west/north west flow across the country with windspeeds increasing during the second half of Thursday (15th) and during Friday (16th) to 10-14m s^{-1} from the west. There was some intermittent rainfall during Thursday evening and early Friday morning but temperatures were mild. During Saturday (17th) the wind backed towards the south by the end of the day, with windspeeds falling to between 7 and 9m s^{-1} . It was cloudy throughout the day with some rainfall during the evening. On Sunday (18th) a vigorous depression tracked south-eastwards from Scotland to North Germany bringing a very strong northerly airflow across the country. Windspeeds in Birmingham remained around 9m s^{-1} throughout Sunday, Monday and Tuesday(18th, 19th and 20th), apart from a slight lull late on Sunday. The wind direction gradually veered from south-west early on Sunday to north by Monday morning and remained between north and north-west during Monday and Tuesday (19th and 20th). There were frequent rain and snow showers throughout the latter half of the study period (Saturday 17th to Tuesday 20th) and temperatures were low.

Figure 17 shows examples of nitrogen oxide (NO) and nitrogen dioxide (NO_2) measurements at all the sites for a single day, Wednesday 14th February. Measurements inside the building, when available, are also shown as the solid symbols on the plots. All pollutant levels were relatively low, none approached any limit or guideline value. The mean windspeed for 14th February ranged between 3 and 5m s^{-1} up to about midday, after which it fell steadily to about 1m s^{-1} at around midnight. The wind direction remained consistently in the arc 300°-330°. Thus the Walsall and Birmingham Central/CB Building sites were nominally aligned with the wind direction, while the Birmingham Central/CB Building sites and the Birmingham east site were nominally aligned across the wind. To a first approximation at these windspeeds, in the 15 minute averaging time of the sampler the accumulated pollutants from upwind distances of about 1-3km are swept past it. Similarly, the lateral dispersion of pollutants over these distances results in pollutants over a band of about 200-500m across the wind (at this greater distance) being averaged across the sampler. Thus the sampler is averaging pollutant levels over a wedge shaped area upwind of around 0.25-1km^2. These distances correspond to the approximate boundary between neighbourhood and urban scales as defined by Munn.

The NO_2 concentrations showed relatively low levels of fluctuation and some similarity in trends between the sites. The NO concentrations showed quite marked variations during the course of the day and high levels of fluctuation even with 15 minute averaging times. Also, on a visual basis none of the NO concentrations at the sites appeared to show much correlation between one another apart from the broad morning and evening peaks. This applied even to the Birmingham Central and CB Building sites, which were only about 500m apart. Here levels of NO_2 were generally higher at the Birmingham Central site, while levels of NO were lower.

The question of what might constitute a 'background' level of pollutants for these sites is clearly not a fixed matter. The implication of the term 'background' is of some lower limit below which levels do not usually fall, though other definitions have been used for different purposes. In practice this can only be expressed on some statistical basis which will depend upon the application. For example, a 'background' pollutant level for the West Midlands area, encompassing all the sites, might be defined as the common level of pollutant that occurs at all sites, that is the lowest common denominator of the data. In Figure 17, a lowest common denominator 'background' level is effectively the lowest data point at a given time from any site on the plot. All the sites contribute to this minimum at some point. For NO_2, where the level of fluctuation is relatively low, the 'background' on this definition usually comprises a significant proportion of the overall concentration at any site. For NO, however, where the level of fluctuation is high, the Birmingham East site produced the lowest concentrations most frequently but not consistently. It will also be appreciated that when there are large fluctuations in pollutant level, such a definition would depend upon the data averaging time chosen. As this increases the 'background' level on this definition would tend towards the long term mean.

Thus for individual sites it is difficult to define a 'background' except on the basis of some pollutant level exceeded at a specific frequency, such as a 10%ile, for some particular averaging time.

3.2. Correlations of Pollutant Levels Between the Sites.

In order to quantify the degree to which pollution levels at each site might be related to each other during the week 14-21 February, values of the correlation coefficient (r^2) were calculated between data from pairs of sites for each day and for each pollutant.

This was first investigated with the Birmingham Central and CB Building sites. Since these were the closest it was thought that they ought to show the highest correlations. Initially 15 minute averages were used and each 24 hour period was considered as a whole. Correlation coefficients between the data at the two closest sites, Birmingham Central and the CB Building, were calculated and the values obtained are given in Table 1. It can be seen that, with the exception of the last two days of the period, there is little correlation between pollution levels at these two sites. It was thought possible that the correlation might be greater for longer averaging times, since this would have the effect of smoothing out the high frequency fluctuations that are probably due to more local sources and emphasising the common elements in the two data sets. Two longer averaging periods were investigated, 30 minutes and 1 hour. The correlation coefficients obtained are also given in Table 1. In general, as would be expected, the correlations increased with increasing averaging time, but there are also some instances where the converse occurred. The changes in values of r^2 are

mostly small and there is still only a limited degree of correlation between the two sites. Two cases, one showing higher values of r^2 (increasing with averaging time) and one lower (decreasing with averaging time), are shown plotted respectively in Figures 18 and 19. It is of interest that even with such short spacings between sites, the correlations between the measurements can frequently be negligible.

Table 1. Correlations between Birmingham Central and CB Building for different averaging times.

Date	CO			NO			NO_2			SO_2		
	15 min	30 min	1 hour	15 min	30 min	1 hour	15 min	30 min	1 hour	15 min	30 min	1 hour
Wed, 14.2.96	0.13	0.14	0.17	0.36	0.34	0.40	0.10	0.11	0.14	0.07	0.08	0.12
Thurs, 15.2.96	0.01	0.004	0.01	0.12	0.12	0.10	0.01	0.005	$4x10^5$	0.11	0.13	0.18
Fri, 16.2.96	0.11	0.22	0.29	0.15	0.22	0.27	0.42	0.51	0.64	0.07	0.09	0.12
Sat, 17.2.96	0.001	0.001	0.002	0.001	0.002	0.01	0.10	0.10	0.09	0.05	0.06	0.08
Sun, 18.2.96	0.16	0.21	0.29	0.12	0.23	0.37	0.67	0.69	0.61	0.06	0.07	0.08
Mon, 19.2.96	0.002	0.003	0.004	0.02	0.02	0.03	0.03	0.03	0.03	0.04	0.04	0.05
Tues, 20.2.96	0.52	0.58	0.68	0.47	0.59	0.72	0.58	0.59	0.58	0.13	0.17	0.20
Wed, 21.2.96	0.35	0.52	0.72	0.50	0.57	0.62	0.23	0.29	0.39	0.56	0.52	0.79

The same approach was used to investigate the relationship between the Birmingham Central and Birmingham East Sites, which have a much greater spacing. We examined the correlation between data at the sites for occasions when the wind was largely blowing from the centre towards the east and compared these results with occasions when the wind was perpendicular to this, across the line of the sites. In the former case there may be evidence of pollution from sources close to the central sites travelling to the eastern site and so higher correlations may be obtained by allowing for this travel time. Conversely, in the latter case there may be larger correlations since the contributions in the two areas from more distant sources might be more similar as the area over which these pollutants originate is almost the same.

Two days were identified with wind directions largely from the centre to the east sites (i.e. south-westerlies) - Thursday 15th and Friday 16th. These were compared with three days when the wind was mostly from the north-west and thus blowing across a line between the central and the eastern sites - Wednesday 14th, Monday 19th and Tuesday 20th. Examples of the time series and the correlation plots for NO and SO_2 are given for Thursday 15th in the upper plots in Figure 20, when the wind was aligned between the sites. It can be seen that there is some broad consistency between concentrations at the two sites, resulting in a relatively high correlation.

One further type of correlation was briefly investigated, which was to account for the approximate travel times between the Birmingham Central and East sites. The same periods as before were used for this. Average windspeeds were calculated and the time of travel between the central sites and the east site evaluated, the data for the central sites were then time-shifted by this amount and the correlation coefficients re-calculated. It should be noted that, because 15 minute averages were used, this time shift could only be carried out to the nearest 15 minutes. The lower plots in Figure 20 illustrate the effect of this time-shift. The values of r^2 are given in Table 2. It is evident that overall the time-shifting has little effect on the relationship between the data in the two regions.

The results of all of these calculations for the Central and East sites and for the Central and CB Building sites are given in Figure 21. The correlations between each of the central sites with the east site as well as those between the two central sites are given for each of four pollutants. There is also a division between wind directions broadly aligned between and across the line of the sites. There is little consistency between the results and the correlation coefficients vary considerably. It can be seen that, overall, the higher correlations tended to be when the wind was across the line of the sites.

Table 2. Correlations between Birmingham Central and Birmingham East sites for occasions when wind blowing from central to east - correlations for data as measured and allowing for travel time between sites.

Pollutant	Date	Data as measured	Including time delay
CO	Thursday, 15/2/96	0.09	0.13
	Friday, 16/2/96	0.13	0.02
SO_2	Thursday, 15/2/96	0.4	0.6
	Friday, 16/2/96	0.001	0.008
NO	Thursday, 15/2/96	0.45	0.23
	Friday, 16/2/96	0.46	0.58
NO_2	Thursday, 15/2/96	0.4	0.3
	Friday, 16/2/96	0.8	0.7

4. DISCUSSION.

It will be appreciated from both the initial discussion and from the example data analysed above that the prediction of pollutant concentrations at specific sites in urban areas is not a perfectly straightforward matter. However, the way in which different sources, especially at varying distances, contribute to the overall levels at a particular site, and the causes of variability in these levels can be understood. The sample data analysed here comprised only a snapshot of pollution characteristics over a short period. However, this is sufficient to show that wide variations in shorter term pollution levels over even quite short distances in urban areas can be expected as a matter of course. Data from monitoring sites is valuable as an indicator of trends in pollution levels and as an indicator of longer term pollution levels over a wider area, but its ability to predict local variations, both spatially and temporally at other places is limited. Most monitoring equipment has a relatively slow response, of the order of minutes and thus fails to record the quite substantial fluctuations that can occur over shorter time scales. Similarly the use of dispersion modelling to predict the pollution characteristics over large areas is mainly confined to relatively coarse grids, usually of kilometre or greater scale, and to longer term averages (one hour is the minimum period and much longer time averages are more common). Information on these small scale variations is presently quite limited. There is a need for pollution monitoring investigations in urban areas which look at both very short term variations in pollution levels and the spatial variation over short distances.

From the point of view of the needs of a specific site, it is clear that data from monitoring sites even relatively close by can only be certain indicators of broad based, long-term pollution levels and that more detailed data, especially if shorter term variations are of interest, would require site-specific investigations.

5. CONCLUSIONS.

1. The paper has outlined the way in which pollutant sources, especially from varying distances, contribute to different features of the total concentration at a point. Both spatial and temporal variations of pollutant concentration can be large and generally increase with reducing averaging time and spatial scale.

2. An investigation of a sample of data from four sites in the West Midlands confirms these characteristics, with significant levels of temporal fluctuation and spatial variation over relatively short distances. Correlations of data between different sites frequently show negligible correlation, even over short distances or relatively long averaging times.

5. ACKNOWLEDGEMENTS.

This investigation was carried out as part of the POLIS project (on integrated urban planning) in the EC JOULE 95 research programme. It was part funded by the Construction Directorate of the UK Dept of the Environment.

Thanks are due to Geoff Broughton and Jon Bower of NETCEN for supplying the shorter time averaged data from the National Network sites in the West Midlands.

6. REFERENCES.

AEA Technology(1995). Air Pollution in the UK: 1994.
AEA Technology, Report No AEA/RAMP/200015001/1.
ISBN 0-85356432 9.

Anon(1996). Road Traffic Responsible for Most Air Pollution.
Pollution, Vol. 26 No. 11, November. Front Page.

Benarie M.M.(1980). Urban Air Pollution Modeling.
The MIT Press, ISBN 0 262 02140 4.

Cook N.J.(1985). The Designers Guide to Wind Loading of Building Structures. Part 1.
Butterworths. ISBN 0 408 00870 9

Cook N.J.(1990). The Designers Guide to Wind Loading of Building Structures. Part 2.
Butterworths. ISBN 0 408 00871 7

Dabbert W.L., Ludwig F.L., Johnson W.B. Jr(1973). Validation and Application of an Urban Diffusion Model for Vehicular Pollutants.
Atmospheric Environment, Vol 7, pp603-618.

EEC(1985). Council Directive 85/203/EEC of 27 March 1985 on Air Quality Standards for Nitrogen Dioxide.
Official Journal of the European Communities, No. L87/1

EPAQS(1995). Sulphur Dioxide.

Report of the Expert Panel on Air Quality Standards. UK Dept of the Environment. HMSO, ISBN 0 11 753135 9.

Georgii H.W., Bush E., Weber E.(1967) Investigation of the Temporal and Spatial Distribution of Emission Concentration of Carbon Monoxide in Frankfurt/Main.
University of Frankfurt/Main, Institute for Meteorology and Geophysics, Report No. 11.

Hall D.J., Kukadia V.(1994). Approaches to the Calculation of Discharge Stack Heights for Odour Control.
Clean Air, Vol 24, No. 2, pp.74-92.

Hall D.J., Kukadia V., Spanton A.M., Walker S., Marsland G.W.(1996a). Concentration Fluctuations in Plumes Dispersing Around a Building - A Wind Tunnel Model Study.
Building Research Establishment, Report No CR 16/96.

Hall D.J., Spanton A.M., Macdonald R., Walker S.(1996b) A Review of Requirements for Simple Urban Dispersion Models.
Building Research Establishment, Report No CR 77/96.

Hall D.J., Spanton A.M., Kukadia V., Walker S.(1996c). Exposure of Buildings to Pollutants in Urban Areas - A Review of the Contributions from Different Sources.
Building Research Establishment, Report No CR 209/96.

Hoydysh W.D., Dabbert W.F.(1994). Concentration Fields at Urban Intersections: Fluid Modeling Studies.
Atmospheric Environment, Vol. 28, No. 11, pp. 1849-1860.

Jones C.D.(1983). On the Structure of Instantaneous Plumes in the Atmosphere.
Journal of Hazardous Materials, Vol. 17, pp.87-112.

Jones C.D.(1996). Something in the Air.
The Chemical Engineer, 28th November, pp. 21-26.

Kukadia V., Palmer J.(1996). The Effects of External Atmospheric Pollution on Indoor Air Quality.
Paper Presented at the 17th AIVC Conference, Gothenberg, Sweden, September 1996.

Kukadia V., Palmer J., Littler J., Woolliscroft R., Watkins R., Ridley I.(1996). Air Pollution Levels Inside Buildings in Urban Areas: A Pilot Study.
Paper Presented at the CIBSE/ASHRAE National Conference, Harrogate, UK, September 1966.

Munn R.E.(1981). The Design of Air Quality Monitoring Networks.
Macmillan. 'Air Pollution Problems' Series. ISBN 0 333 30460 8.

Oke T.R.(1987). Boundary Layer Climates.
Routledge. ISBN 0 415 04319 0.

Ott W.R.(1977). Development of Criteria for Siting Monitoring Stations.
Journal of the Air Pollution Control Association, Vol. 27, No. 6, pp.543-547.

QUARG(1993). Urban Air Quality in the United Kingdom.
First Report of the Quality of Urban Air Review Group. UK Dept of the Environment.
ISBN 0 9520771 1 6.

Schwela D, Zali O. (1999). Urban Traffic Pollution.
E & FN Spon. ISBN 0 419 23720 8.

Timmis R.J., Walker C.A.(1989). Dispersion Modeling of the Effect of Smoke Control on Air Quality in Kirkaldy.
Warren Spring Laboratory, Report No. LR729.

Vignatti E., Bercowicz R., Hertel O.(1996). Comparison of Air Quality in Streets of Copenhagen and Milan, in View of the Climatalogical Conditions.
The Science of the Total Environment, Vols. 189/190, pp467-473.

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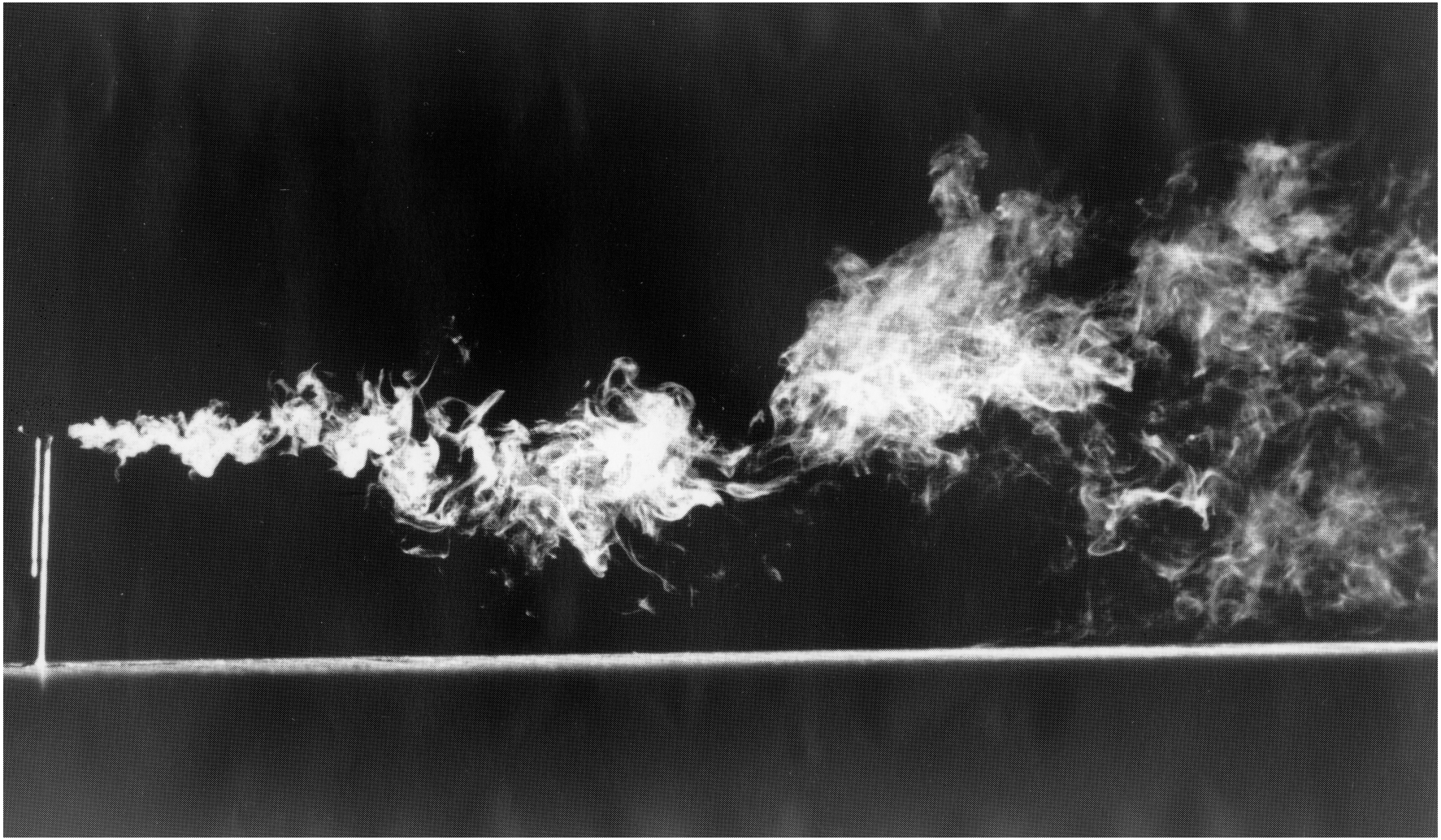


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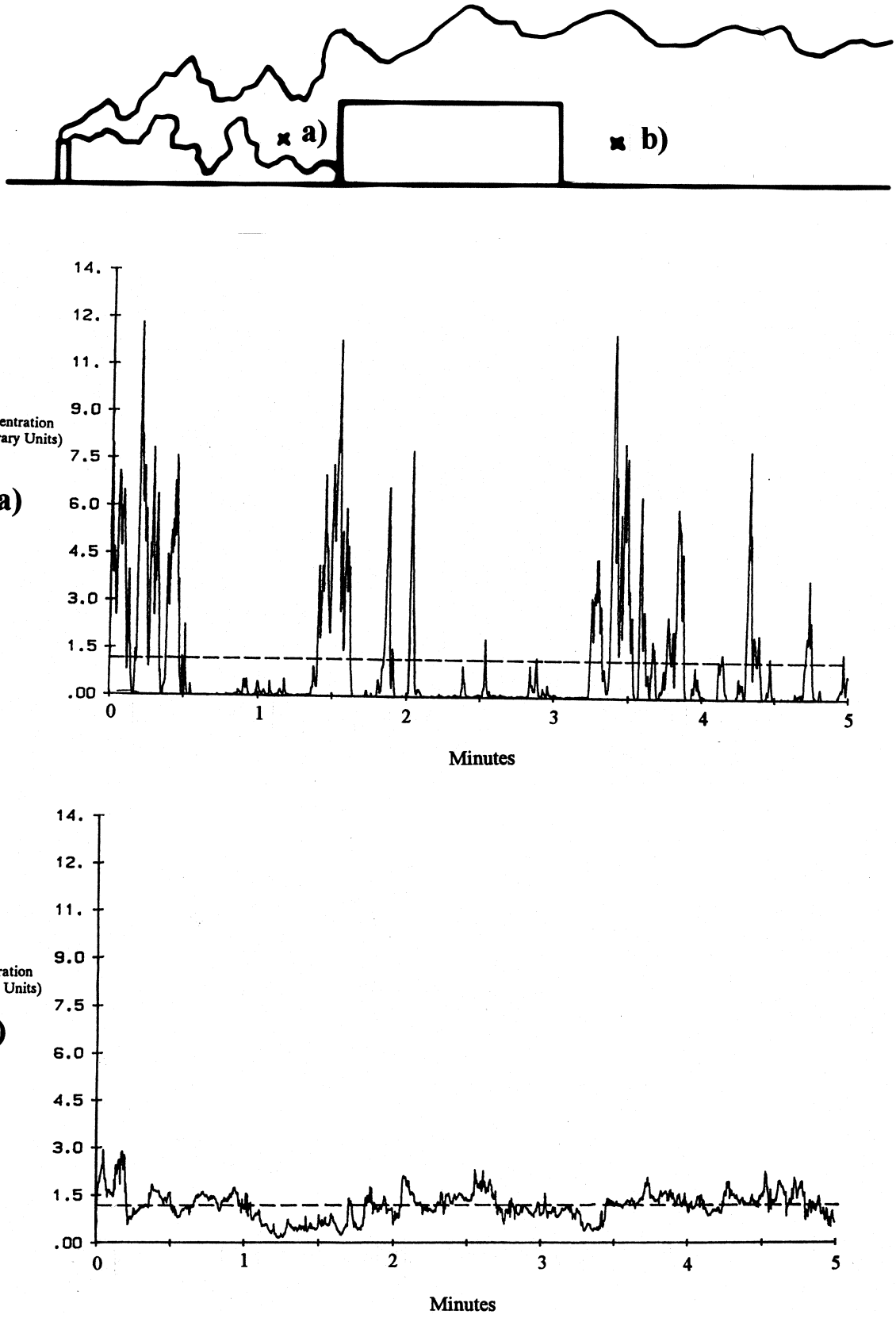


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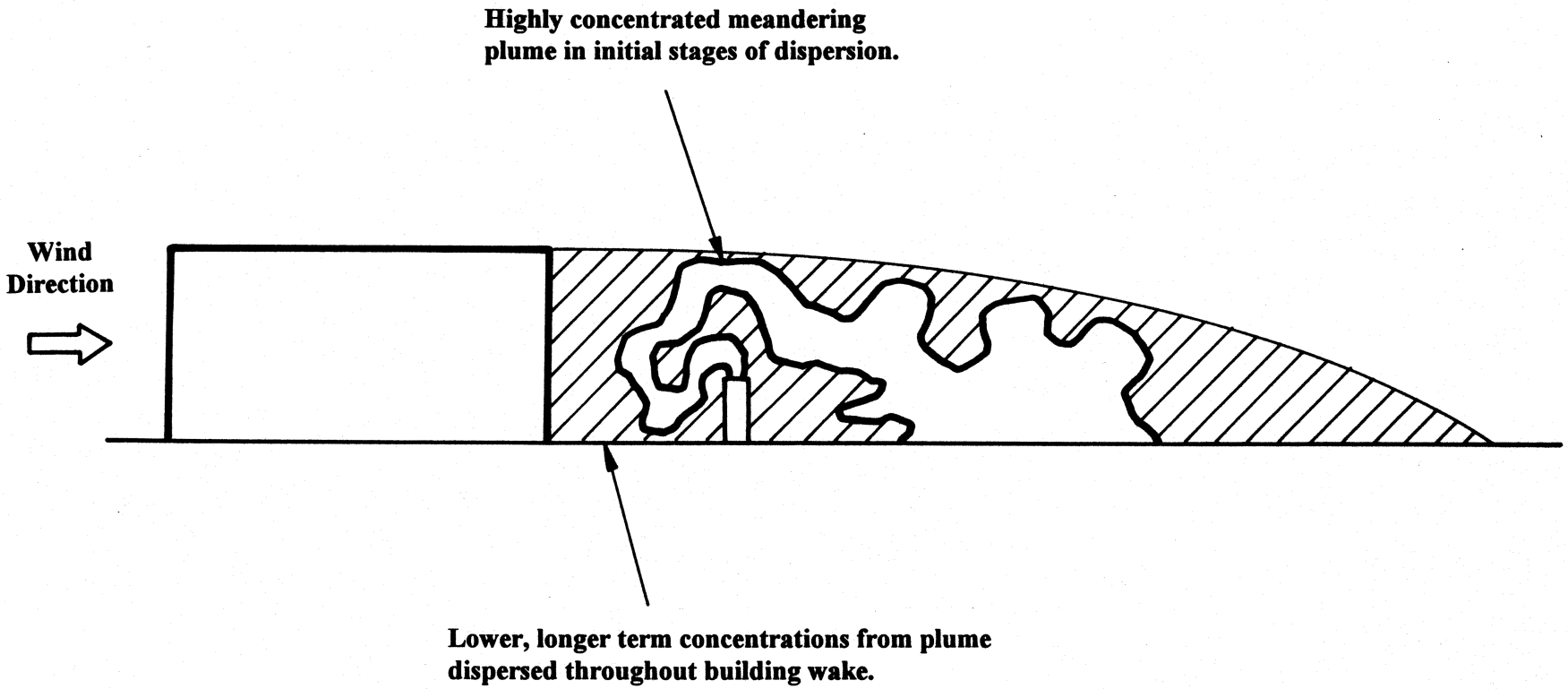


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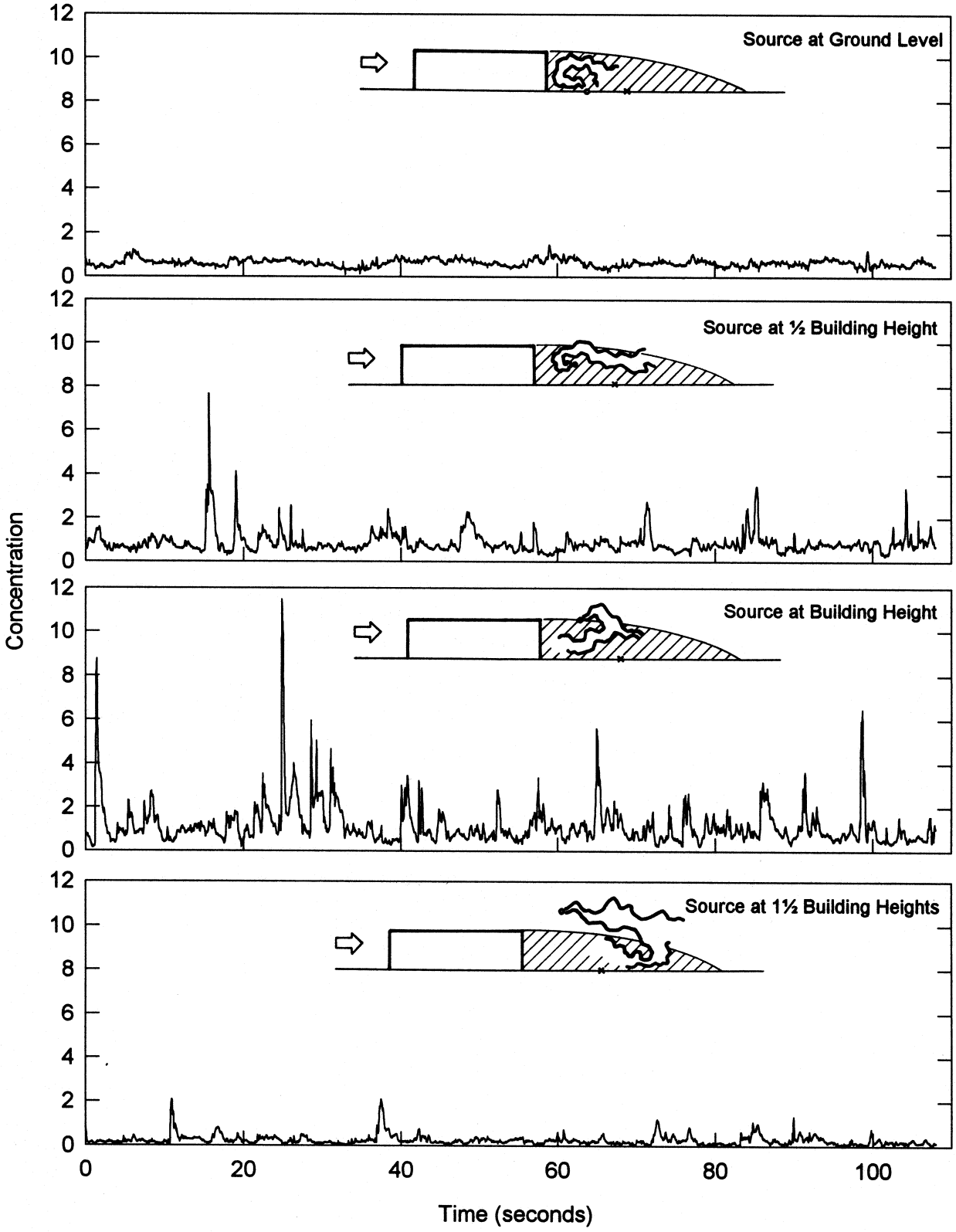


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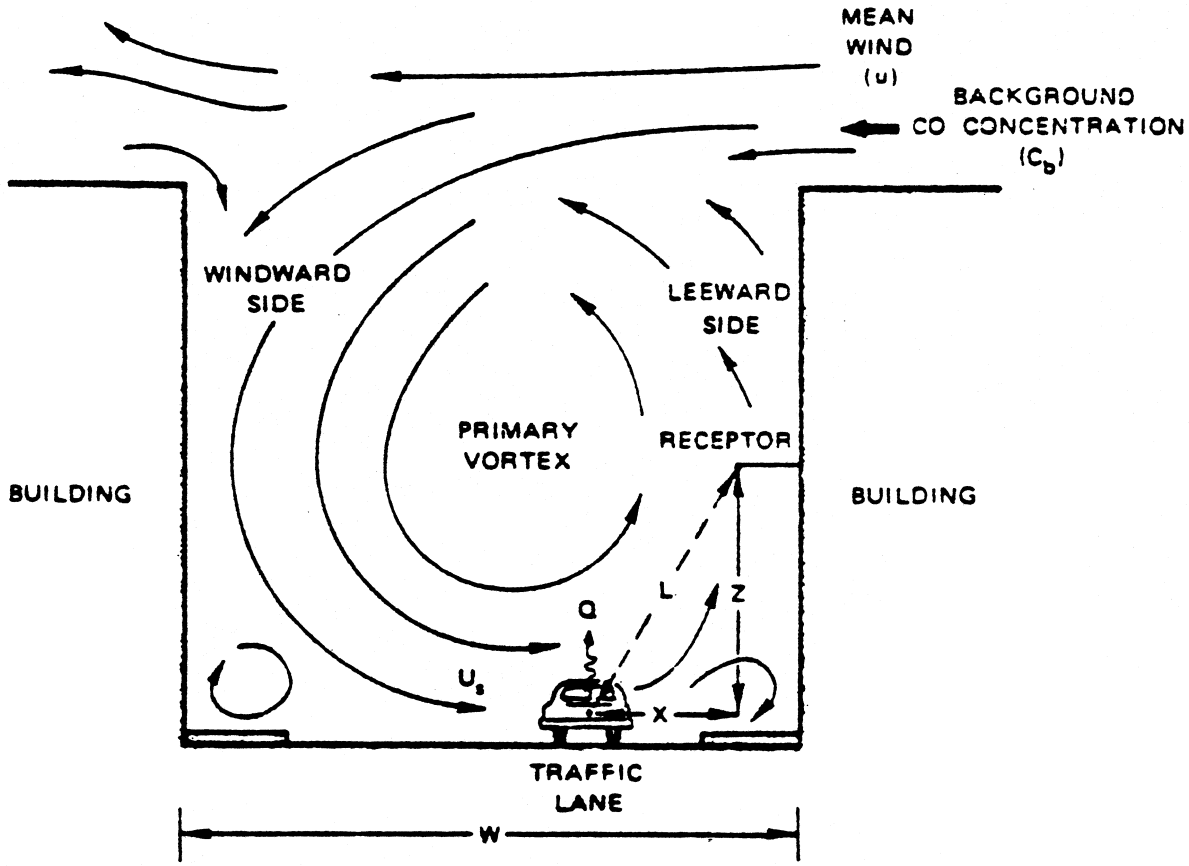


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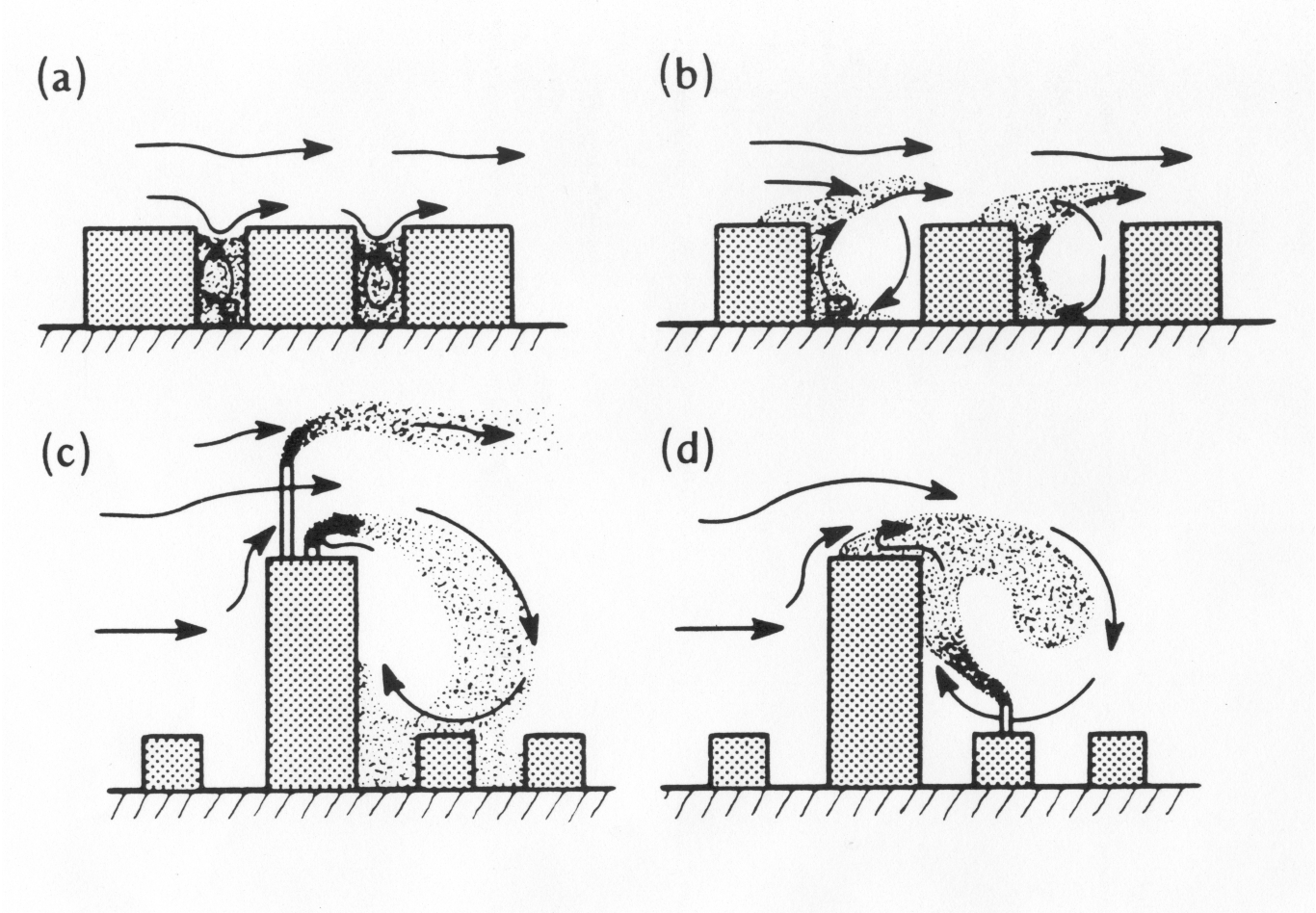


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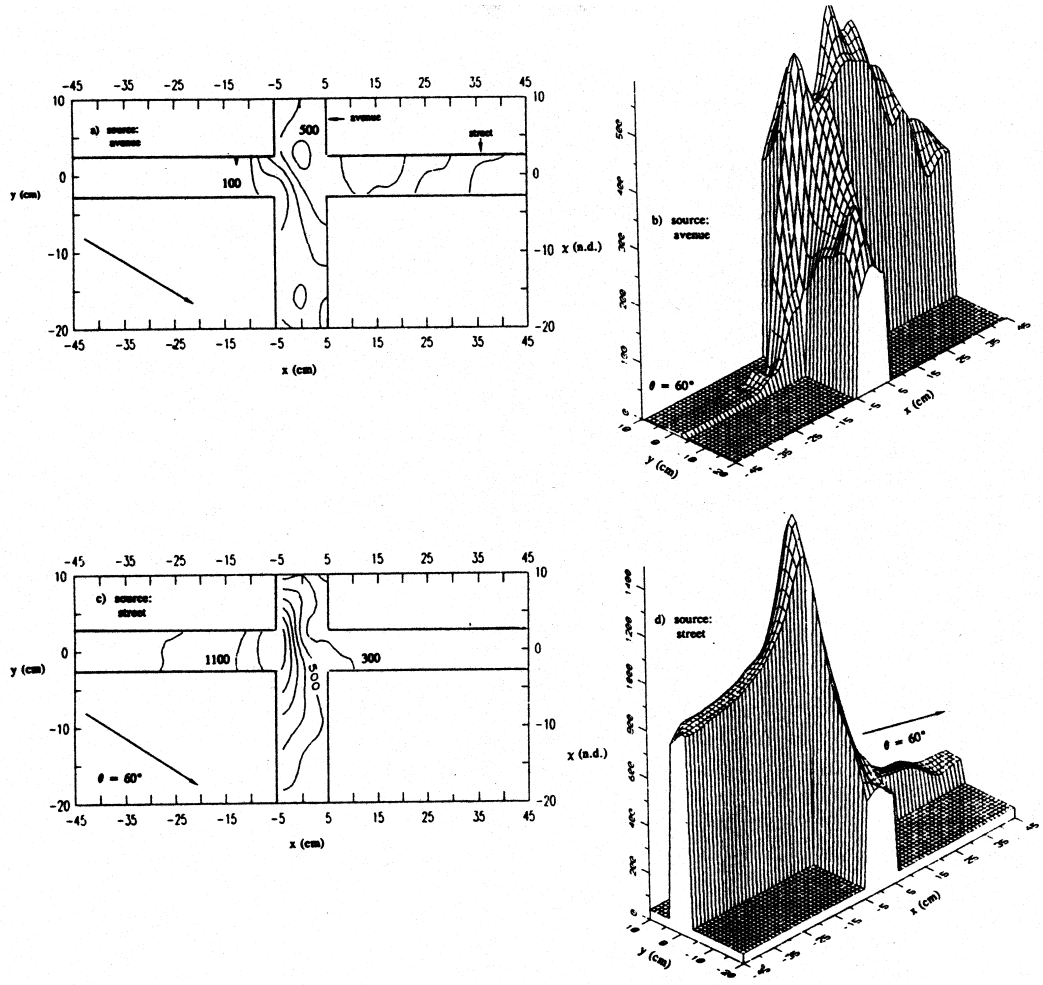


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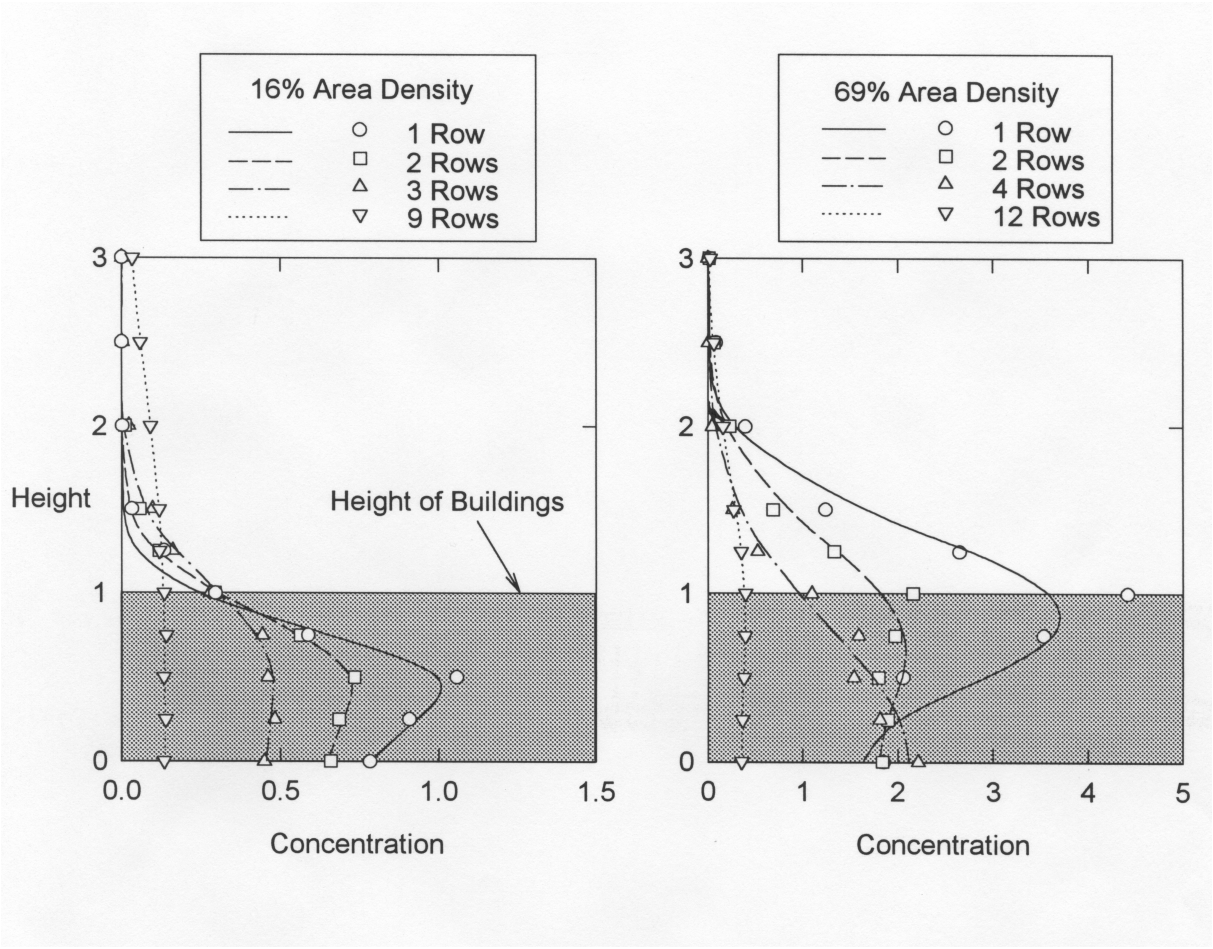


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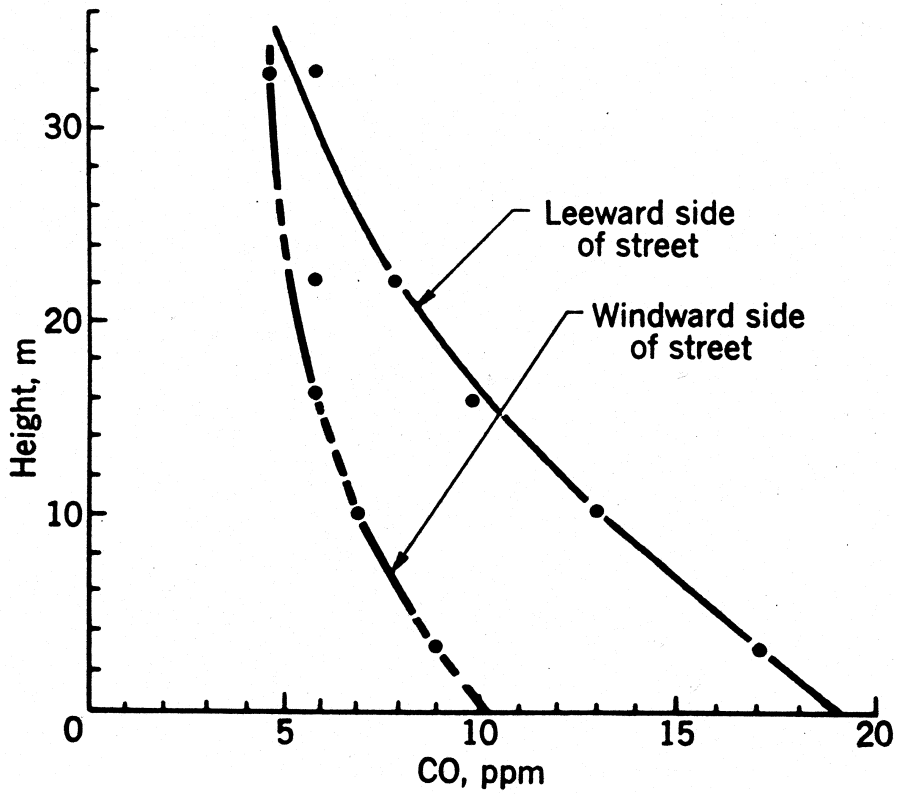


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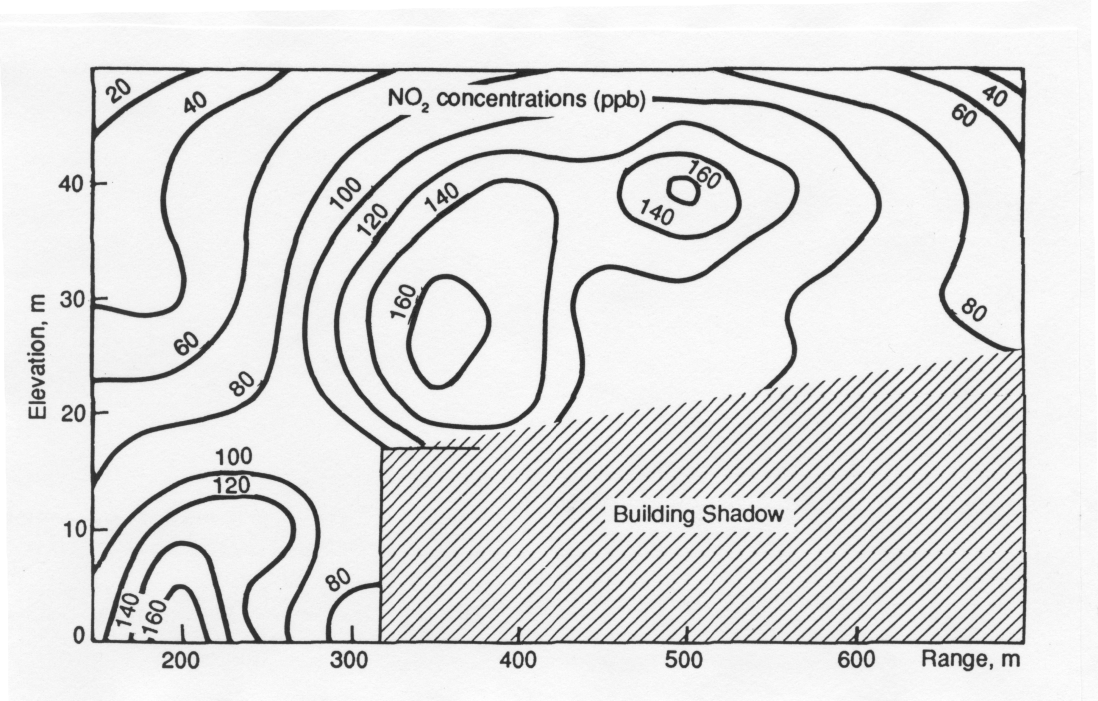


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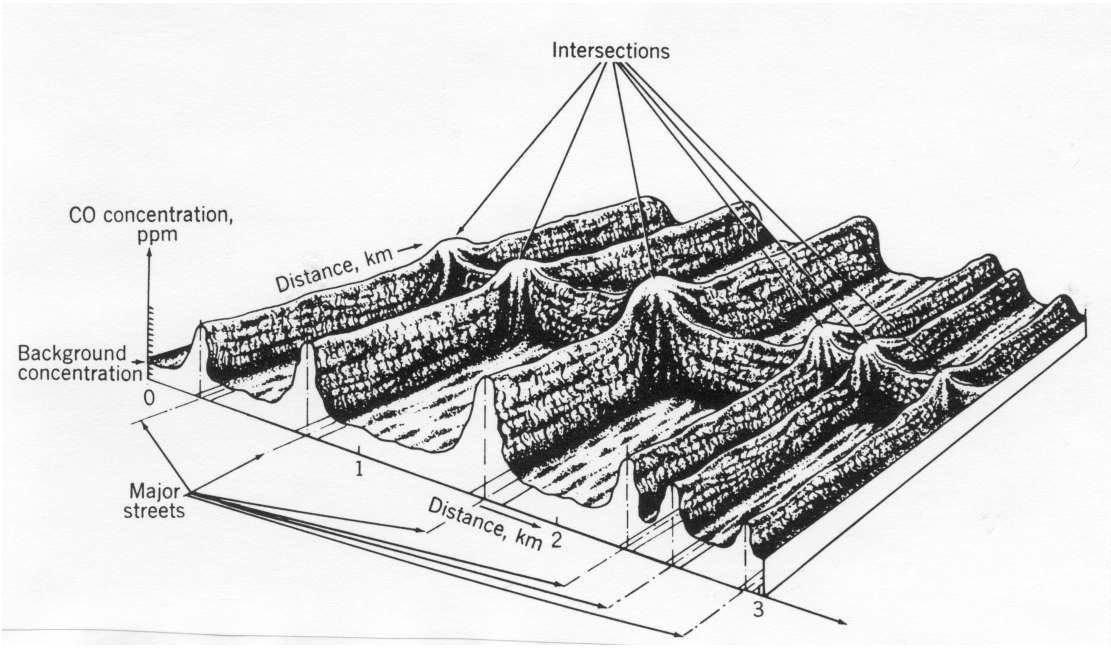


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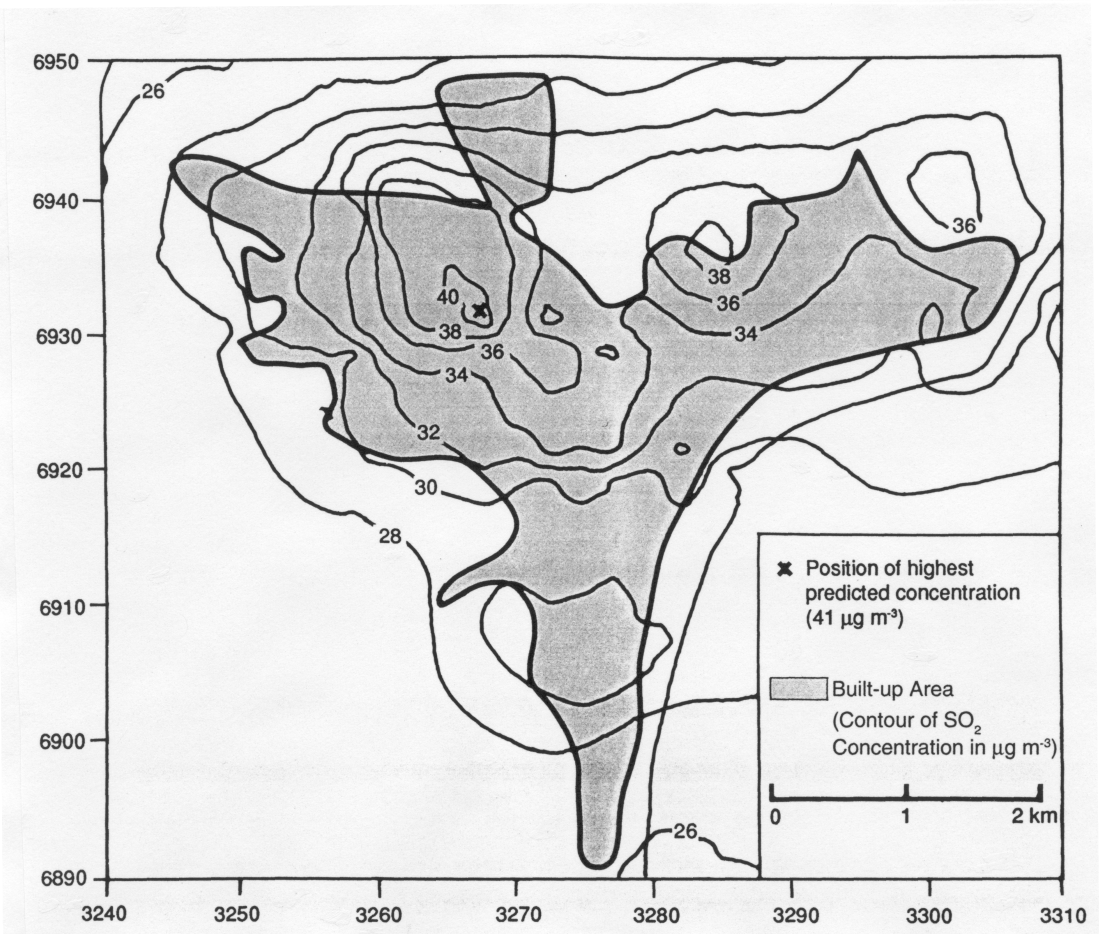


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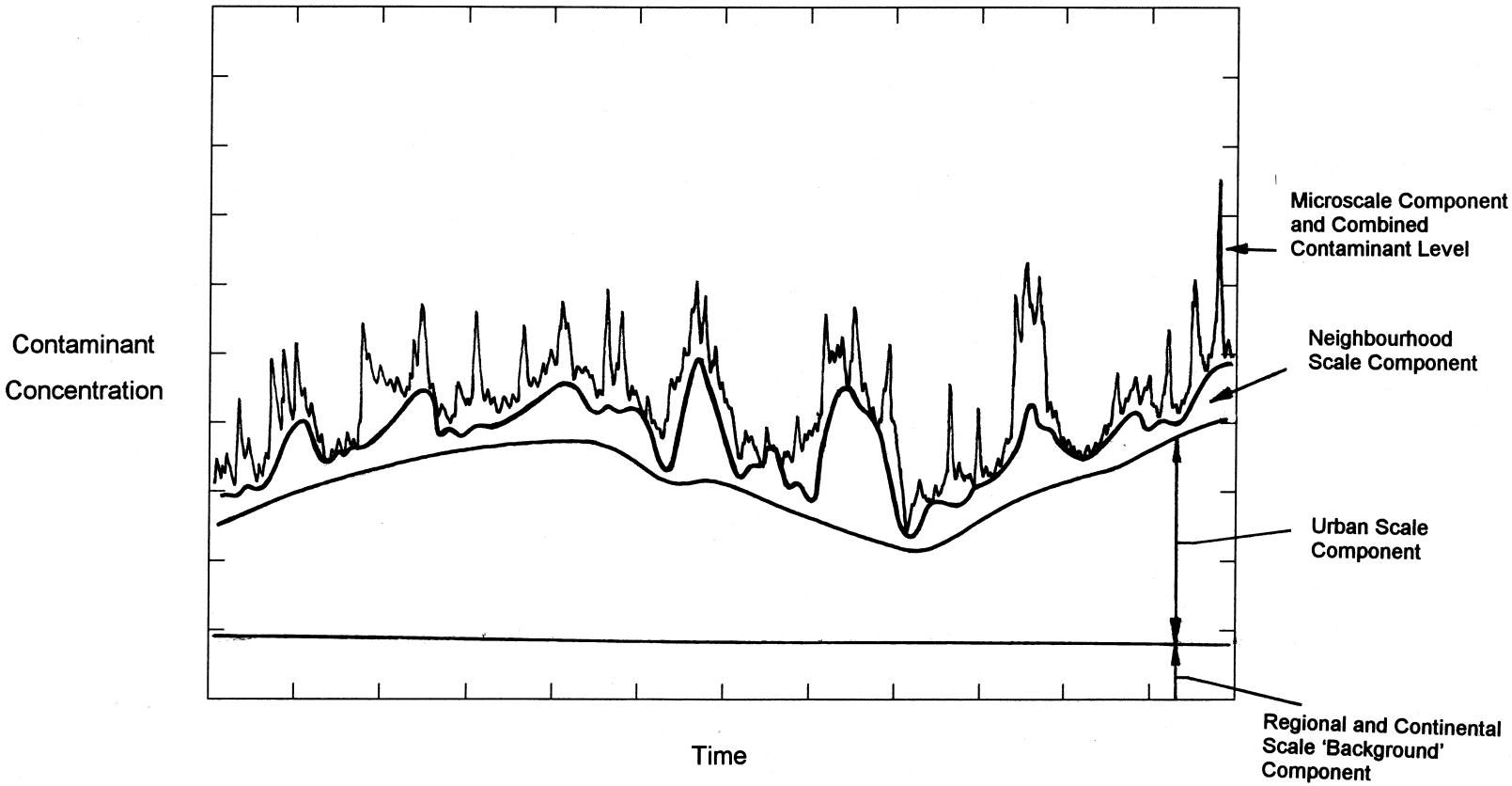


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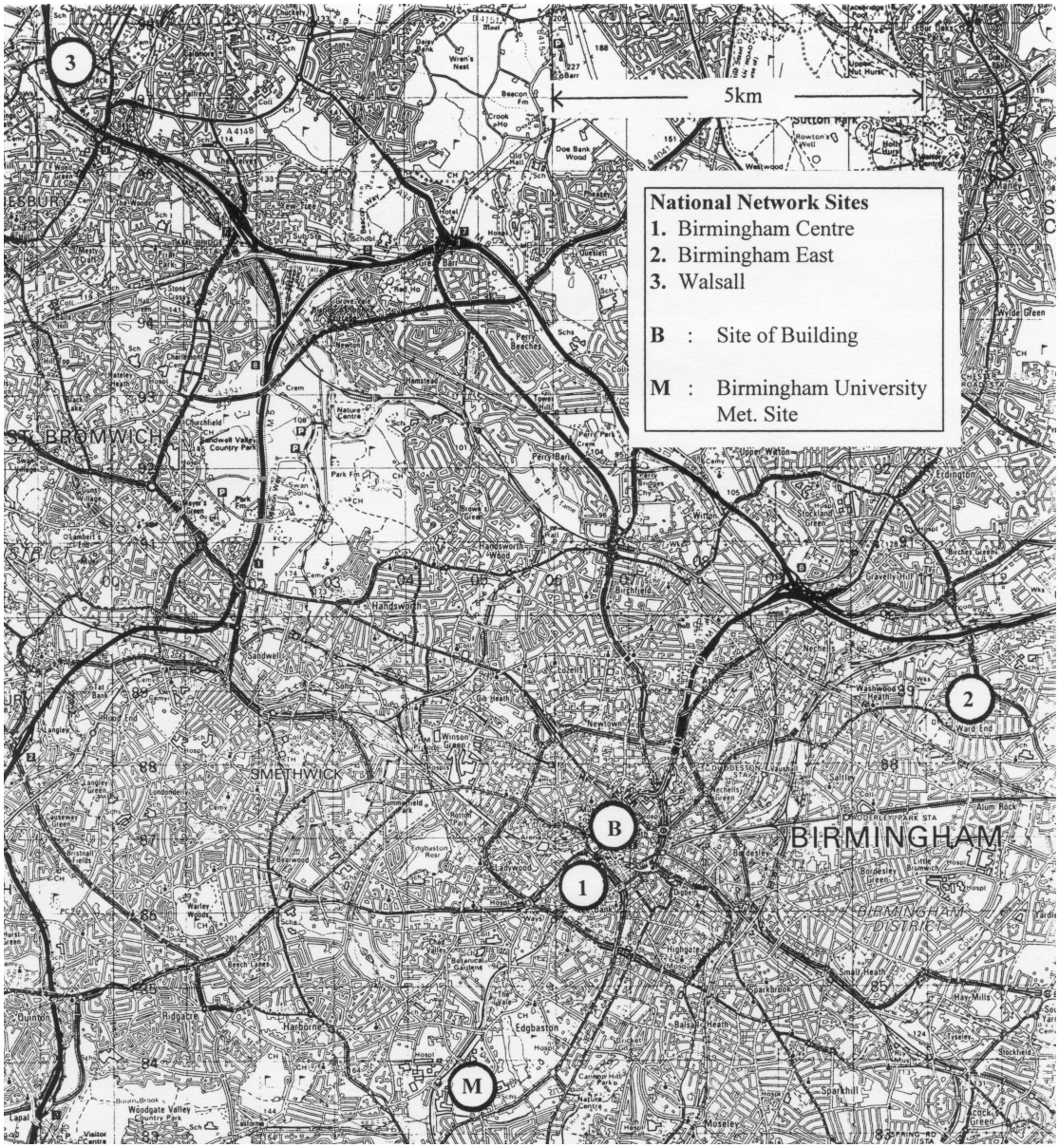


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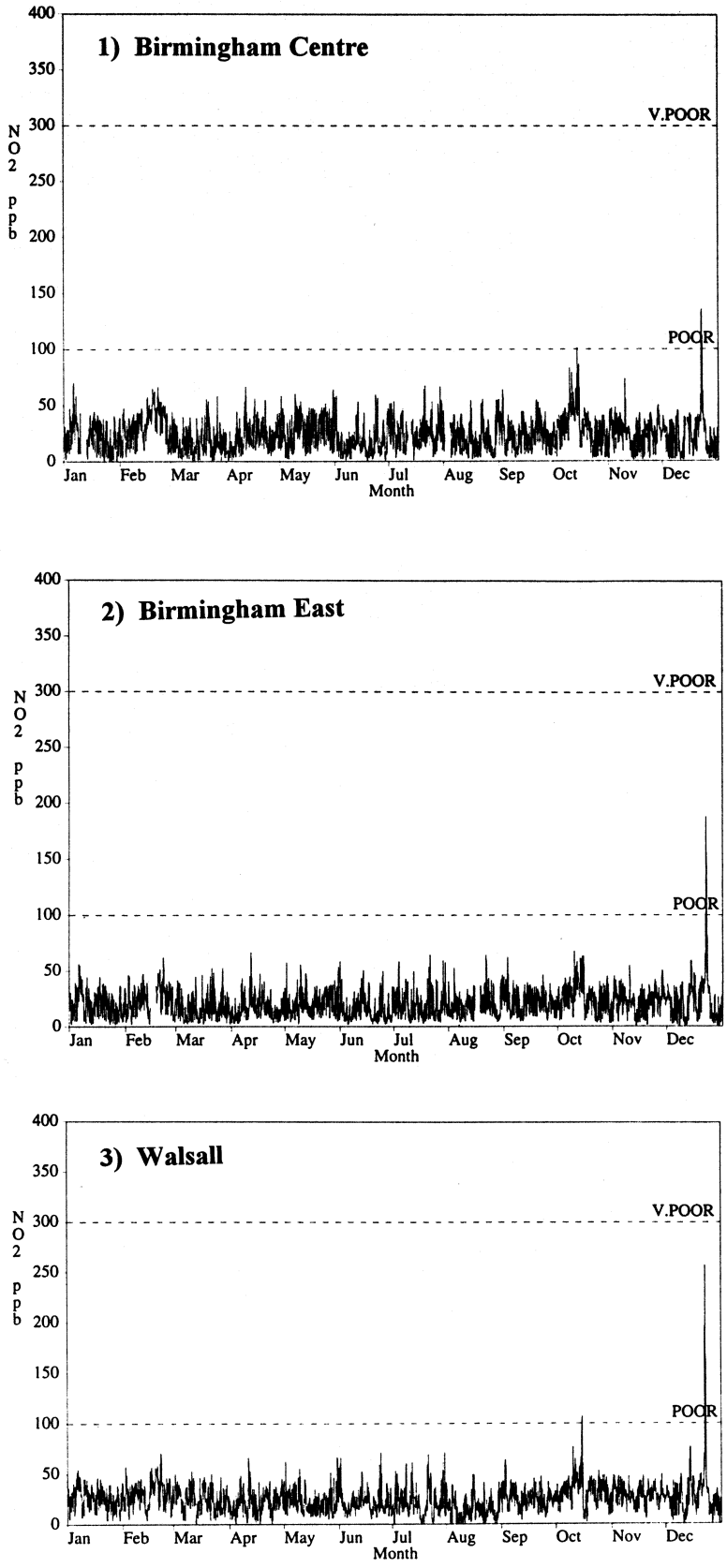


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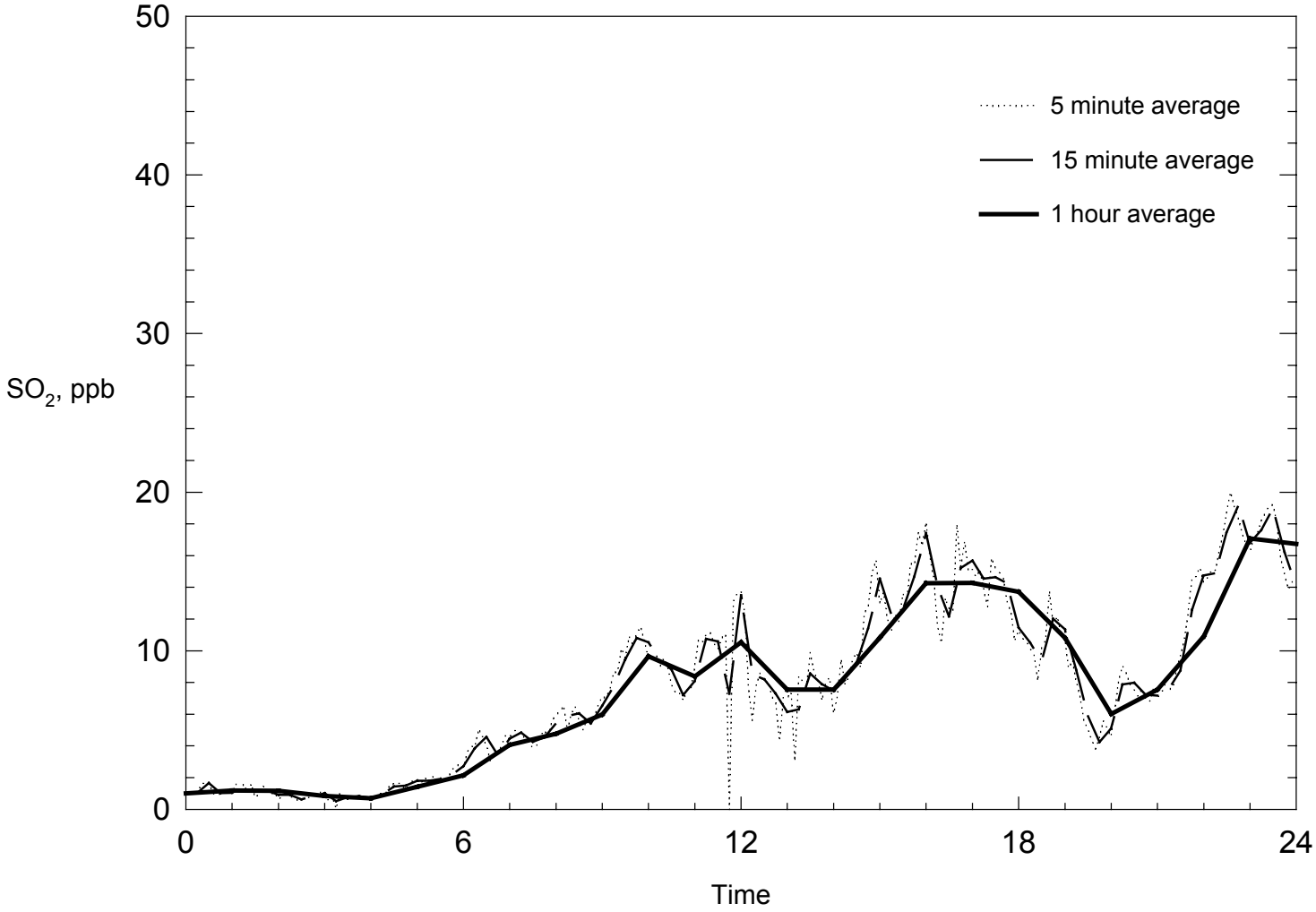


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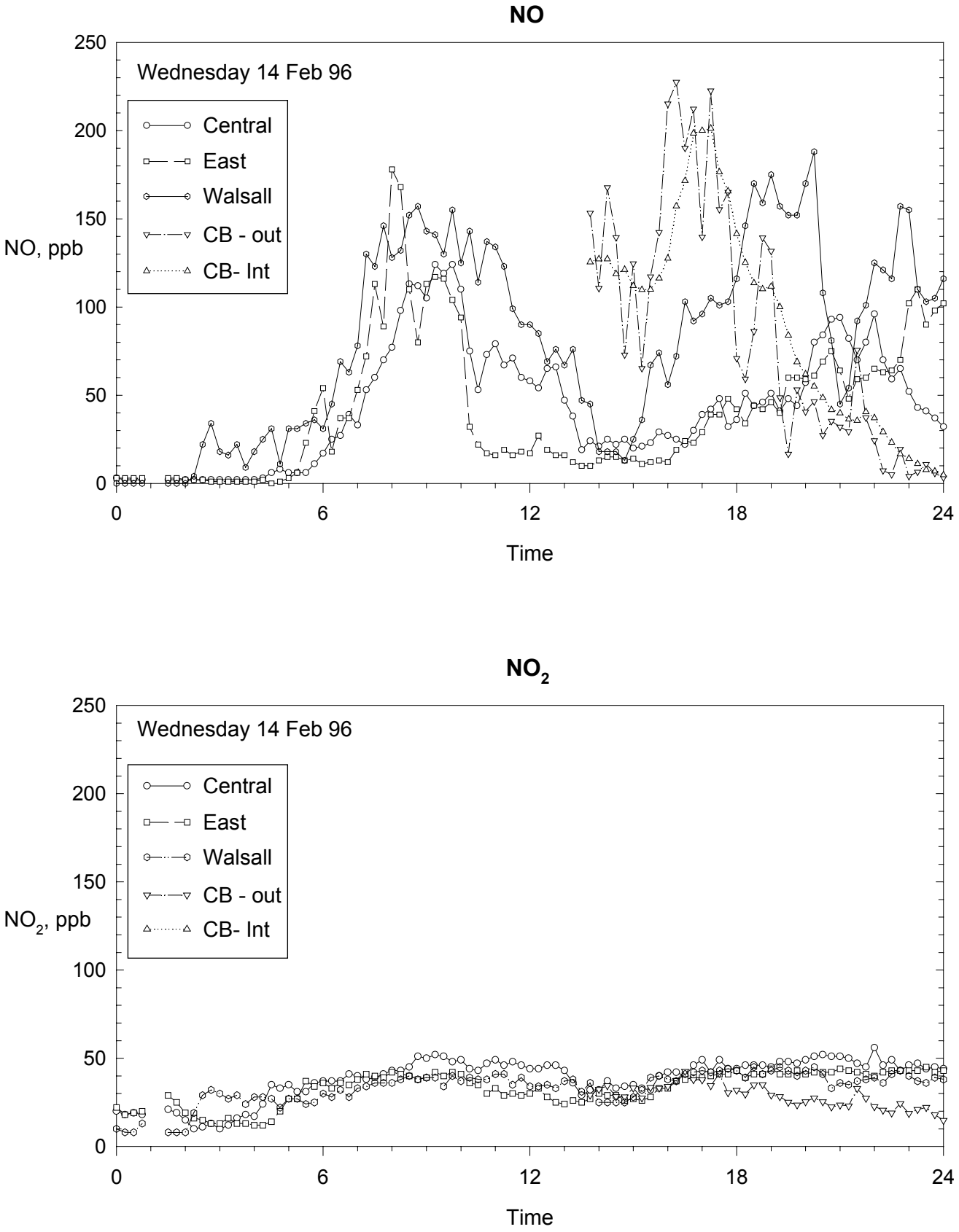


Figure 17. Measurements of NO and NO_2 for a Single Day, Wednesday 14th February. 15 Minute Means.

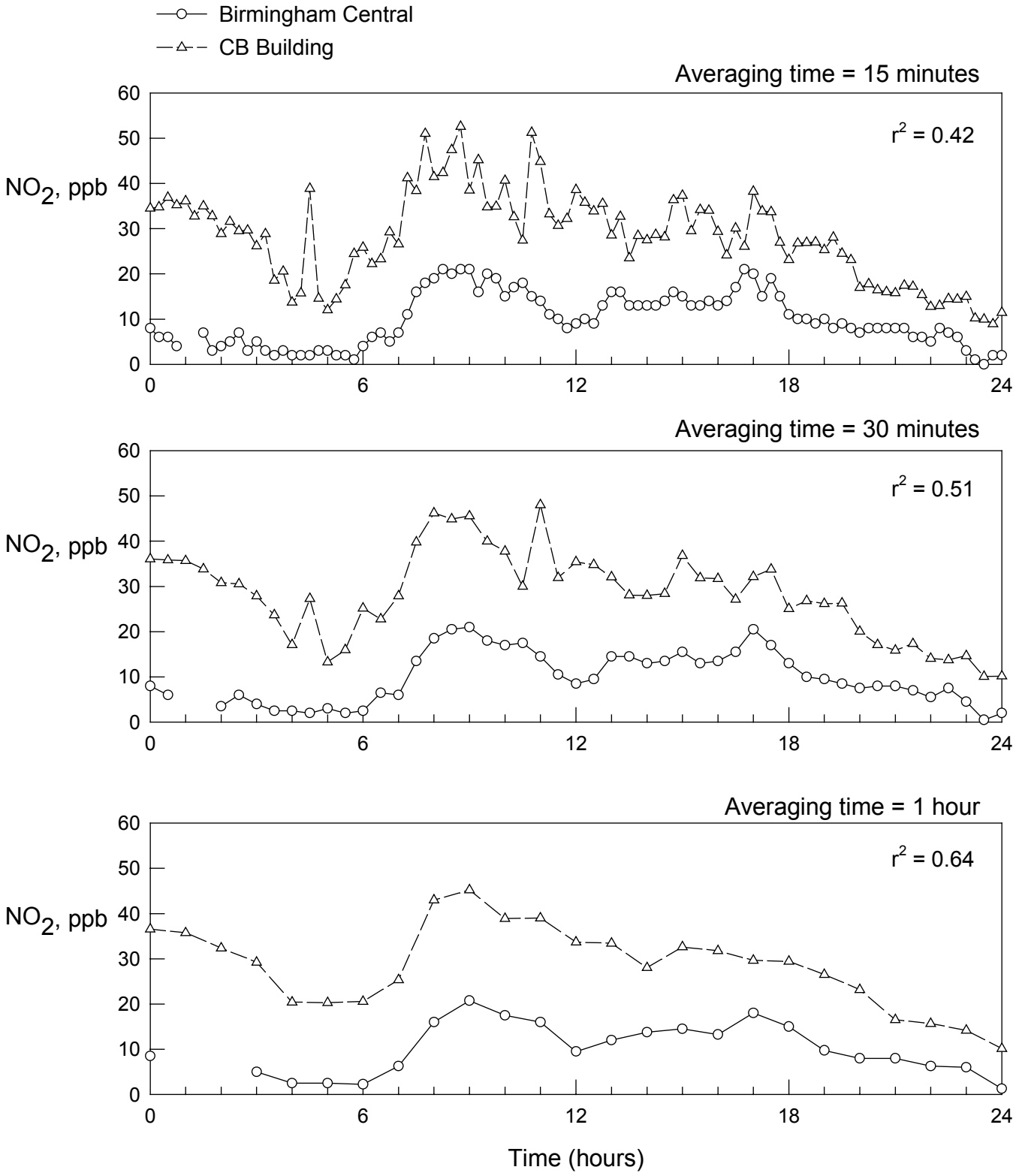


Figure 18. Correlations between NO_2 Concentrations at the Birmingham Central and CB Building Sites for Different Averaging Times. Data for a Period with High Correlation, 16th February.

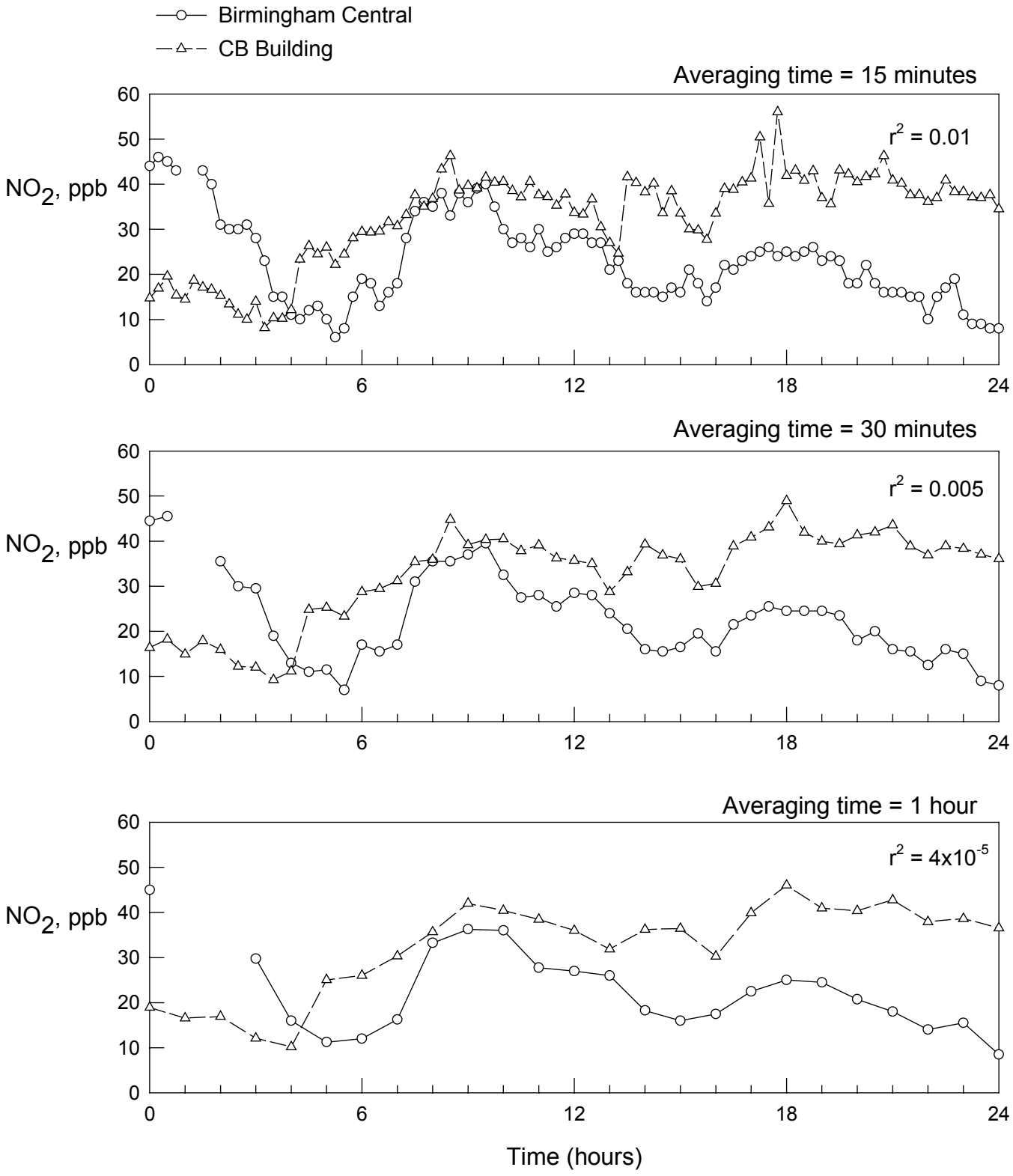


Figure 19. Correlations between NO_2 Concentrations at the Birmingham Central and CB Building Sites for Different Averaging Times. Data for a Period with Low Correlation, 15th February.

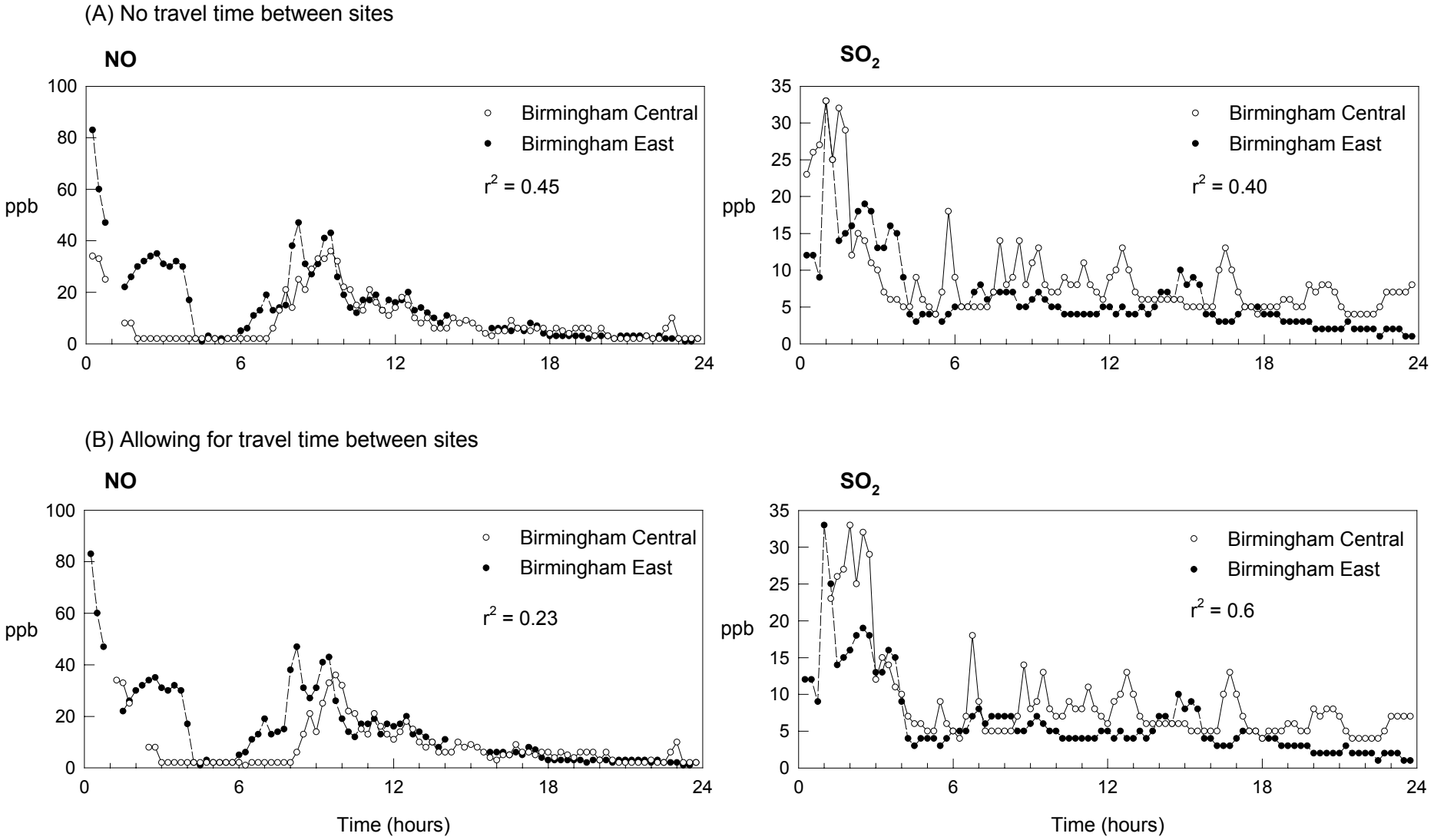
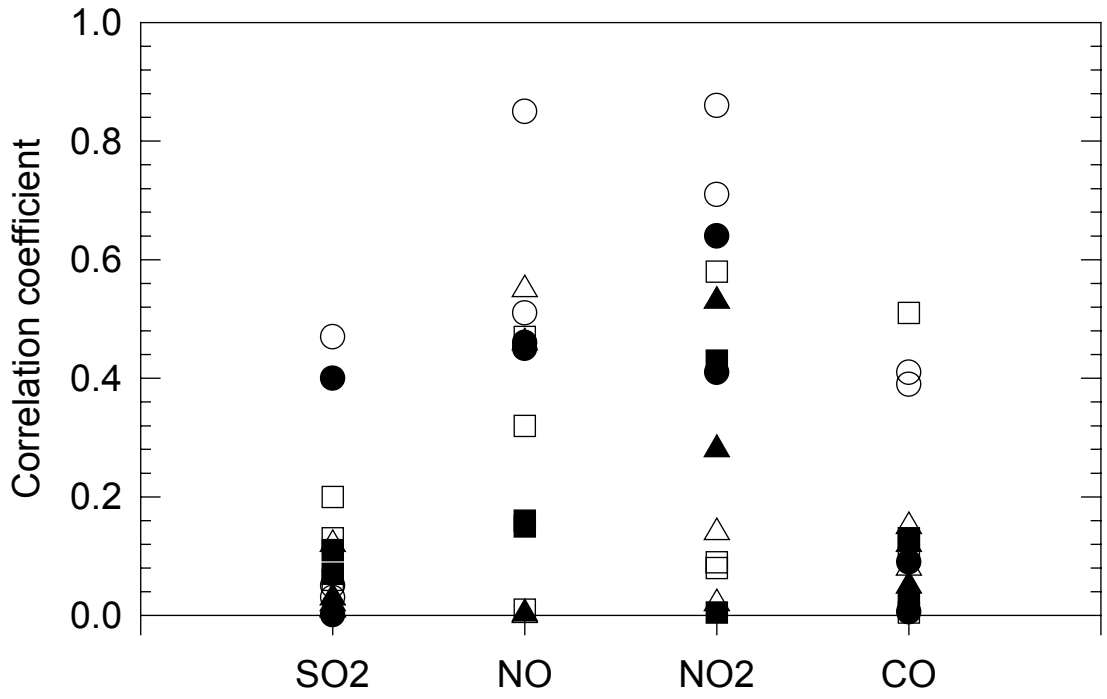


Figure 20. Correlations for NO and SO_2 Concentrations between Birmingham Central and East Sites with an Aligned Wind, 15th February.



Correlations

- ● Central and East Birmingham Sites
- ■ Central Birmingham and CB Building sites
- ▲ CB Building and East Birmingham sites

Filled in symbols are for occasions when wind direction along line of sites (~250^{o})

Open symbols are for occasions when wind direction across line of sites (~340^{o})

Figure 21. Overall Correlation Coefficients between Birmingham Central, CB Building and Birmingham East Sites for All Pollutants.