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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.

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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. 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

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. 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(1996a) who discuss these problems in more detail.

The relationship between pollution levels at these different scales is the subject of discussion here. 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.

The present paper is taken from a longer work, by Hall et al(1996a), which considers these matters in more detail.

DISPERSION OVER DIFFERENT SCALES IN URBAN AREAS

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 to some extent 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 problem. In a discussion of 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

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.

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 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.

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.

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. A 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 itself, 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 1 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

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 2, 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 3, 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

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 structyures and their immediate surroundings, as is more the case with microscale dispersion patterns.

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 1a to one more resembling that of Figure 1b. With increasing distance the diffusing effects of larger numbers of buildings come into play and the variability further reduces.

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. 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. 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) 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 3 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 4 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. Here , there are both positive and negative vertical concentration gradients depending upon the detailed circumstances of the discharge and its surroundings.

There seem to be few field measurements of the vertical gradient of pollutants in urban areas. Measurements by Georgii et al(1967) of carbon monoxide (CO) on either side of a street showed falling concentration with increasing height. Since vehicular traffic is the major source of CO, the measurements are largely for a distributed, ground-based source. Figure 5 (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.

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.

Figure 6, taken from Ott (1977), shows a hypothetical example of the distribution of urban pollution from traffic sources.

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 comprised 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. Ott's diagram in Figure 6 includes a base level of background pollutant concentration to which the local sources additionally contribute.

The Overall Pollutant Concentration Level Due to the Contribution of Sources at Varying Scales and 'Background' Concentrations.
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 7 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.

CONCLUSIONS.
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.

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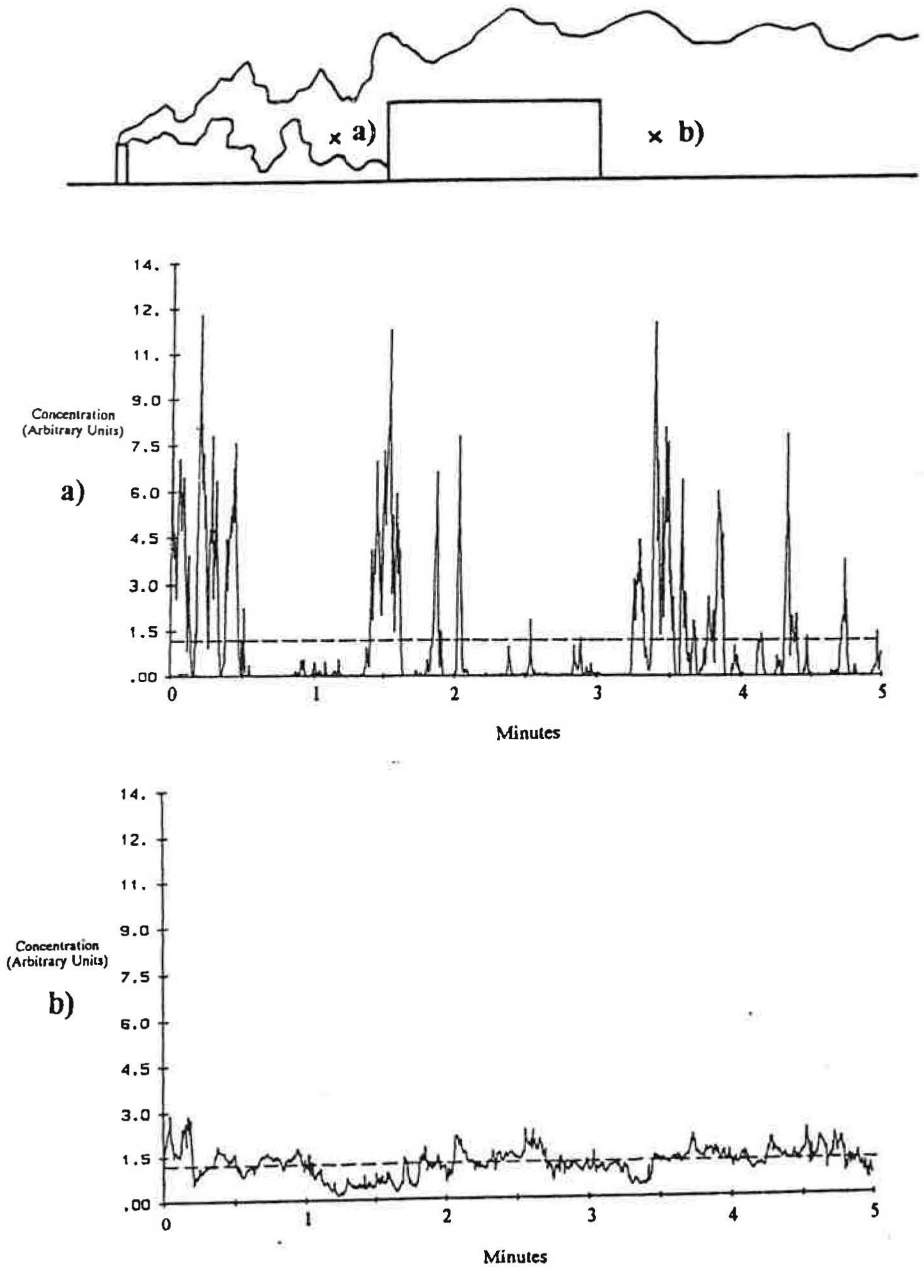

Figure 1. Concentration/Time Measurements of the Pollutant in a Plume Dispersing at Short Ranges Near a Rectangular Building.
a) In the Undisturbed Plume Just Upwind of the Building.
b) In the Wake Region in the Lee of the Building.

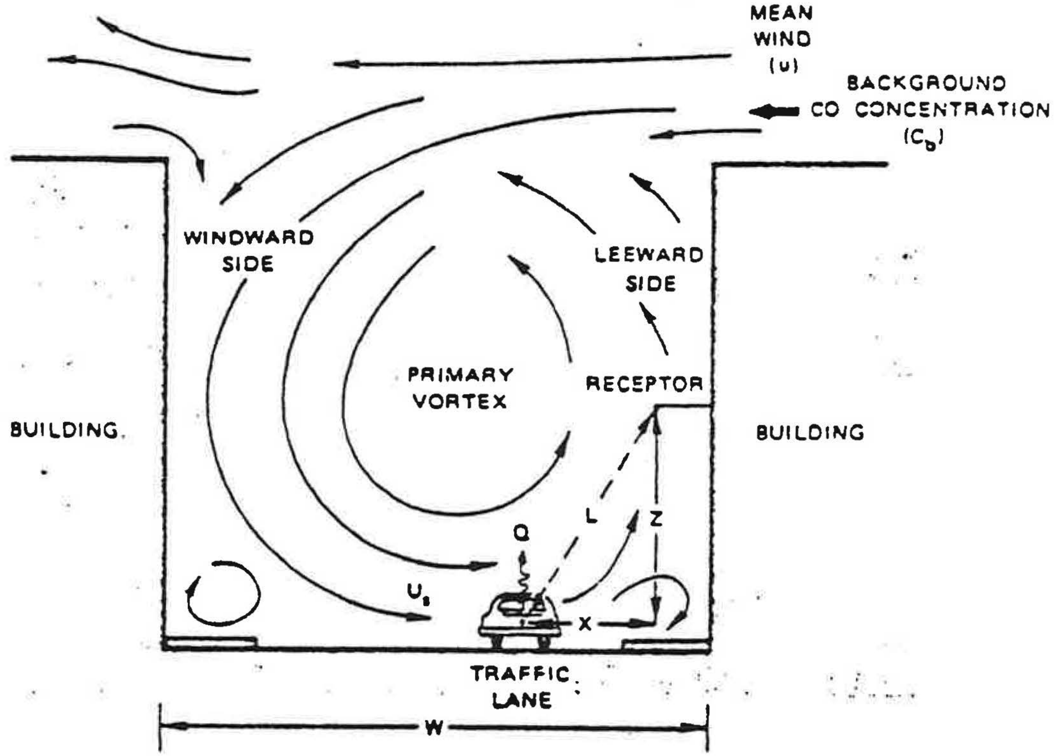

Figure 2. Simplified Flow Pattern in a Street Canyon. From Dabbert et al(1973).

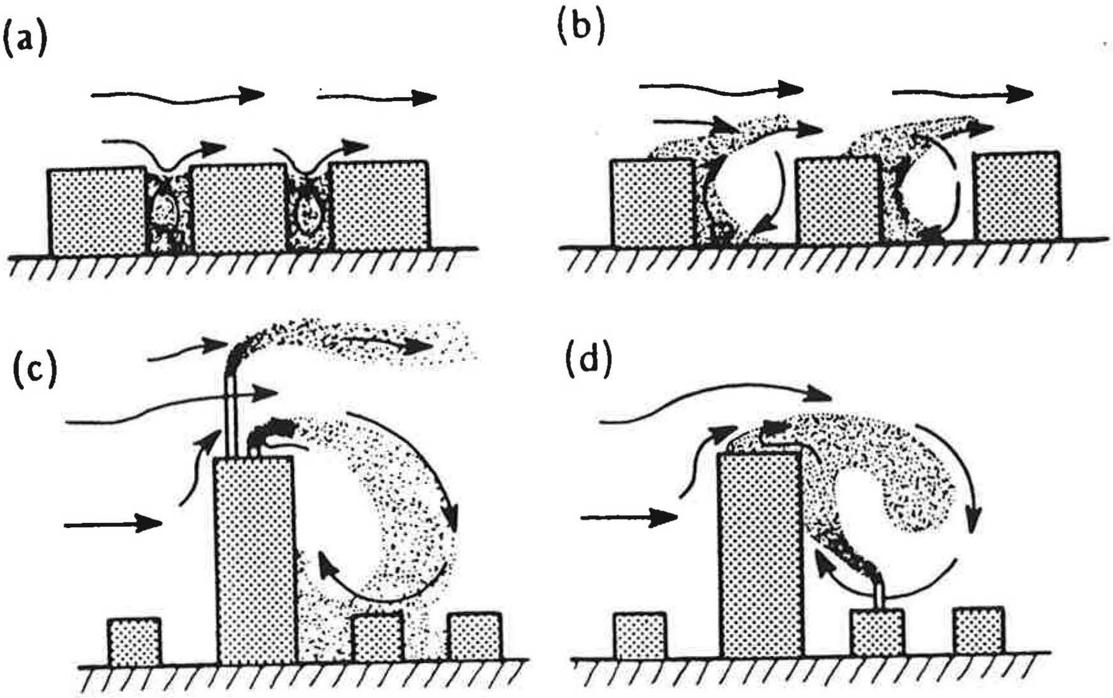

Figure 3. Potential Pollutant Plume Paths at Short Ranges from Sources in Urban Areas. From Oke(1987).

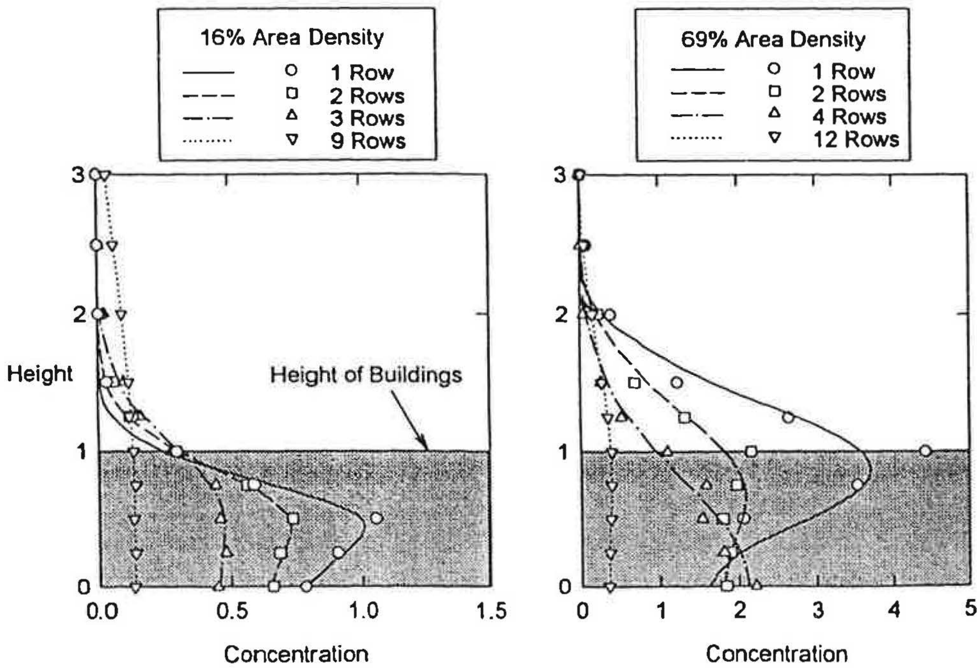

Figure 4. Vertical Profiles of Pollutant Concentration at Different Distances Through Simulated Urban Arrays with Two Different Densities of Building Occupation, 16% and 69%.

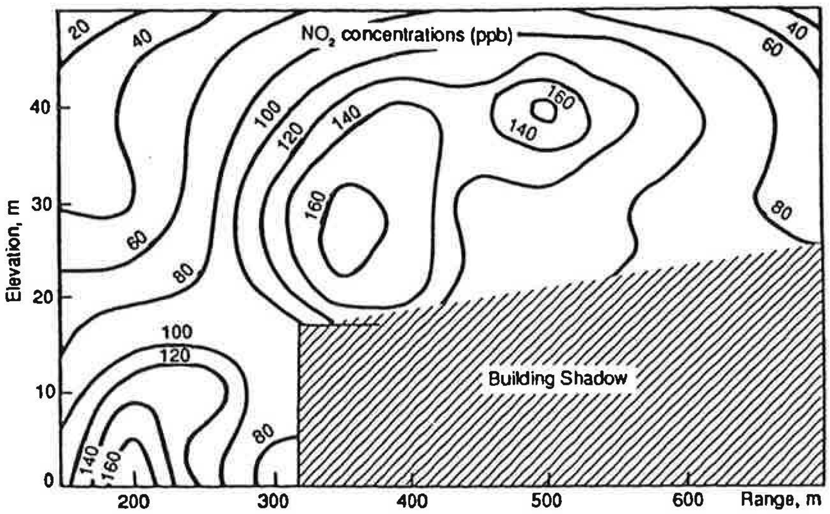

Figure 5. Remotely Sensed Contours of NO_2 in a London Street with Dense Traffic. From QUARG(1993)

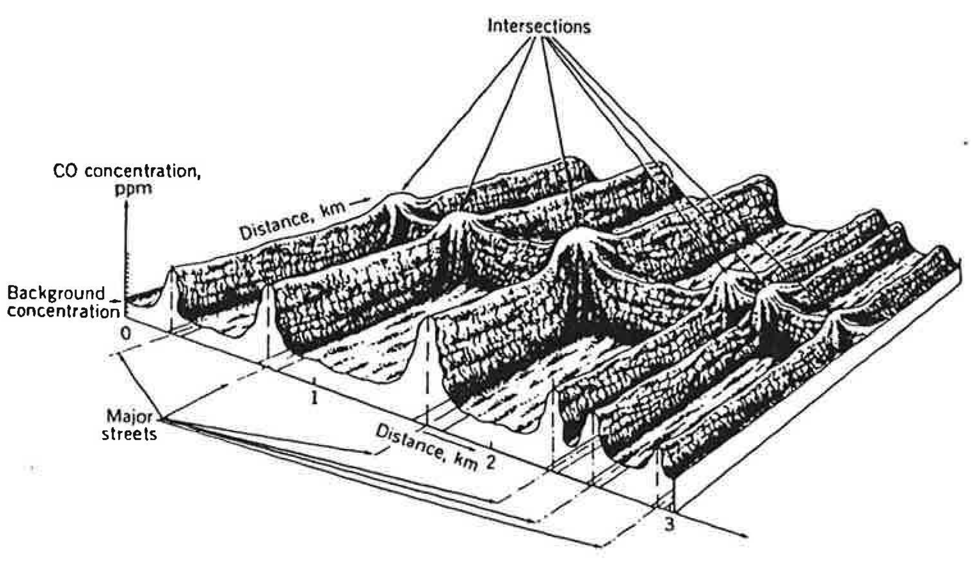

Figure 6. Hypothetical Map of Urban Pollutant Levels from Vehicular Traffic on a Grid of Streets. From Ott(1977).

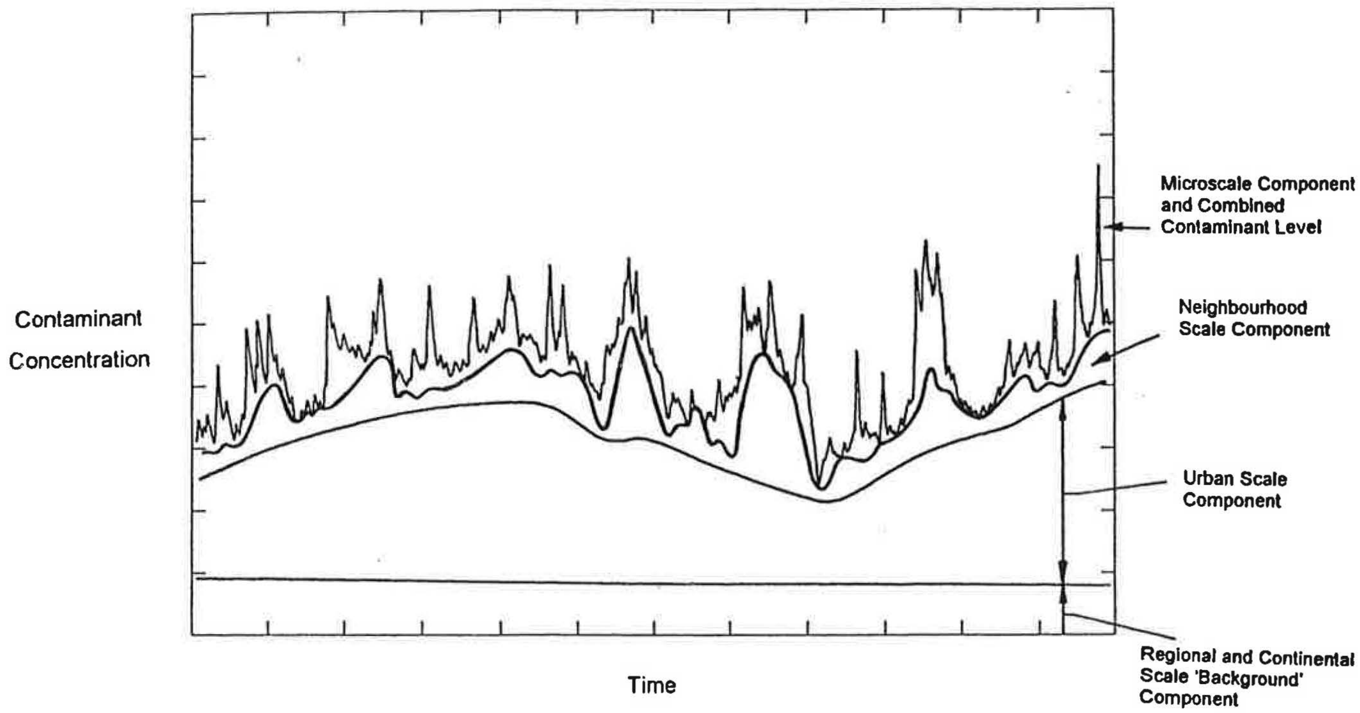

Figure 7. Hypothetical Example of the Contributions of Pollutants from Different Source Regimes to the Combined Pollutant Level at a Point.