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**Research Report TM/96/09**
**1996**

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World Health Organisation
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# *Dispersion of Traffic Pollution from Street Canyons in Edinburgh*

*A Searl and D Buchanan*

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INSTITUTE OF OCCUPATIONAL MEDICINE

# DISPERSION OF TRAFFIC POLLUTION FROM STREET CANYONS IN EDINBURGH

by

A Searl and D Buchanan

FINAL REPORT

Duration of project: October 1994 - January 1996

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**INSTITUTE OF OCCUPATIONAL MEDICINE**

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**IN EDINBURGH**

**by**

**A Searl and D Buchanan**

**SUMMARY**

The IOM was sponsored by The Scottish Office to look at the effect of the canyon-like topography of streets in Scottish cities on the dispersion of traffic pollution. In particular there was concern that the retardation of the dispersion of traffic pollution by tall buildings in some central city streets may be sufficient to have an adverse effect on the health of those who live or work in these streets.

The first stage of the project involved a literature review to assess the likelihood of the canyon-like topography of Scottish city streets having a significant effect on local air quality. Model simulations do suggest that the dispersion of traffic pollution may be retarded by streets with similar aspect ratios to some Edinburgh streets. The greatest build-up of pollutants would be expected in streets perpendicular to the wind with maximum concentrations arising at street level on the sheltered side of the street. Measurements of traffic pollution in other cities have not, however, unequivocally established the existence of a canyon effect. Some reports suggest that street geometry has a smaller effect on local air quality than patterns of traffic flow. Edinburgh street canyons are not particularly deep or continuous and any canyon effect is likely to be smaller than in either the model simulations or other cities, where building heights may exceed twenty storeys. Given that the reduction in pollutant concentrations with height above the street, is in proportion to the height of the canyon, even if the canyon effect does arise in Edinburgh, relatively high concentrations of pollution are only likely to arise at street level. In other cities, the same concentrations might extend to four or five floors of a twenty storey building.

The second phase of the project involved measuring indoor and outdoor concentrations of air pollution in two representative street canyons in Edinburgh (Frederick Street and South Bridge). The aims of these measurements were to establish whether the canyon topography of Scottish streets has a detectible effect on the dispersion of pollutants and whether it is likely that pollution concentrations within street canyons exceed national and international guides and limits more frequently than is suggested by routine air quality monitoring data. Further aims were to establish whether the canyon phenomenon has a detectible effect on indoor air quality and to establish whether there is a need to introduce more or less radical changes in traffic control in order to reduce the concentration of pollutants within street canyons.

Measurements of outdoor air quality were made on both sides of each of the two streets involved and at different heights above the streets. Simultaneous measurements of indoor air quality were made in large used and unused open plan offices, a small more traditional office, a building society staffroom, an unused cellar and unused attic. All these indoor locations differed from typical residential premises in that there were no immediate sources of indoor air pollution, for example, from gas appliances or from tobacco smoking. The pollution measurements made were of carbon monoxide concentrations at 2 minute intervals and of daily mean concentrations of particulates, as PM10, nitrogen dioxide, benzene, toluene and xylene.

The carbon monoxide data suggest that there is a detectible canyon effect on the dispersion of traffic pollution, particularly if hourly mean (rather than daily mean) concentrations are considered. The build up of pollutants due to the presence of queuing traffic can, however, have a greater effect on local air quality than the canyon effect with high concentrations of pollution arising, even in relatively open environments.In addition, traffic is only one of several urban sources of air pollution and both the $NO_2$ data and preliminary carbon monoxide measurements indicate that building sources of pollution may be locally significant.

The daily mean outdoor concentrations of other pollutants (nitrogen dioxide, particulates, benzene, toluene, xylene) do not show consistent evidence of a canyon effect, suggesting that traffic sources of these pollutants in some streets are small relative to general urban background concentrations (although the background concentrations may themselves be largely the result of traffic pollution).

The data suggest that national guides and limits for hourly mean and daily mean outdoor concentrations of some pollutants may be exceeded more often in street canyons than at the EUN monitoring sites in Princes Street Gardens and on top of the Medical School. In particular, the EPAQS (1995) guidelines for particulate concentrations measured as PM10 appear to be frequently exceeded in city streets. Daily mean concentrations of other pollutants (nitrogen dioxide) do not appear to be greater in street canyons than at the EUN monitoring sites and the guides and limits for other pollutants (carbon monoxide, benzene) are unlikely to be frequently exceeded.

The indoor air quality data indicate that in the absence of significant indoor sources of pollution, concentrations of gaseous pollutants appear to be similar to outdoor concentrations, whereas concentrations of PM10 are generally much lower than outdoor concentrations. Peak outdoor concentrations of carbon monoxide pollution, particularly when measured over 1 hour rather than 24 hour periods, give rise to higher than normal indoor concentrations, but maximum indoor concentrations of pollutants are less than maximum outdoor concentrations. In rooms that are well ventilated by open windows there is no significant difference between indoor and outdoor concentrations at any instant in time. In less well ventilated rooms the diurnal variation in pollution concentrations lagged with respect to the outdoor diurnal variation.

Indoor air quality in domestic premises may be less directly related to outdoor air than in the premises in which monitoring has been carried out because of the probable presence of significant indoor sources of pollution such as gas-fired appliances, tobacco smoke and solvents present in various household products.

# 1. BACKGROUND AND AIMS

## 1.1 Introduction

The IOM has been sponsored by The Scottish Office to look at the effect of the canyon-like geometry of streets in Scottish cities on the dispersion of traffic pollution. In particular there has been concern that the retardation of the dispersion of traffic pollution by tall buildings in some central city streets may be sufficient to have an adverse effect on the health of those who live or work in these streets. The first phase of the project involved undertaking a literature review to assess the probability of a "canyon effect" retarding the dispersion of traffic pollution from city streets and to inform the second phase of the project (Appendix 1). The second phase of the project involved undertaking measurements to establish whether a "canyon" effect is detectible and whether it is of sufficient magnitude to be of concern, particularly with respect to air quality in city homes. This report describes the results of two measurement campaigns undertaken in Edinburgh during the autumn of 1995 to assess the importance of street and building geometry in governing city air quality.

## 1.2 Summary of Conclusions from Phase 1 (The Literature Review)

The effectiveness with which traffic pollution is dispersed from open roads in rural areas depends principally on the weather. Local concentrations of pollutants are governed by both patterns of traffic flow and dispersion. In urban streets, the presence of buildings may impede the dispersion of traffic pollution leading to the build up of relatively high concentrations of pollutants in narrow city streets flanked by tall buildings. Such streets have been described as canyons and the theoretical retardation of the dispersion of pollutants from such streets as a "canyon effect" (see Appendix 1).

Model simulations performed in wind tunnels suggest that the canyon-like geometry of some Edinburgh streets may retard dispersion of traffic pollution (Fig. 1; Appendix 1). The simulations predict that, for a uniform source of traffic pollution within a street, maximum concentrations are likely to arise in streets that are perpendicular to the wind and have a high height to width ratio. Although the aspect ratio of Edinburgh streets is similar to that used in some of these simulations, there are, however, a number of marked differences between the street geometry of the model simulations and that of Edinburgh streets (Fig 2). The model assumes a simple, flat sky line, whereas the sky line in most streets is broken by buildings of different heights and church spires. The canyon walls in most streets are interrupted by lanes, passages and other entries rather than being smooth and some buildings are set further back from the street than others. The model uses solid blocks between the streets whereas most blocks in Edinburgh are hollow with extensive backgreens between tenements. In business dominated areas, these backgreens may still present as paved areas or have been replaced by relatively low rise buildings. In terms of indoor air quality, this means that the influence of outdoor air, is not restricted to that from the street.

Measurements of traffic pollution elsewhere in the world have not established that the canyon geometry of real city streets generally causes a detectible retardation of the dispersion of traffic pollution (see Appendix 1). Edinburgh street canyons are not particularly deep or continuous and any canyon effect is likely to be smaller than in the model simulations or cities elsewhere in the world where building heights may exceed twenty storeys. The reduction in pollutant concentrations with height above the street, is in proportion to the height of the canyon (Figure 1), so even if the canyon effect does arise in Edinburgh, relatively high concentrations of pollution are only likely to arise at street level whereas in other cities, the same concentrations might extend to four or five floors of a twenty storey building.

Measurements in other cities also suggest that street geometry has a smaller effect on local air quality than patterns of traffic flow (Luria et al, 1990). The existence of significant indoor sources of pollution in most premises (Spangler and Samet, 1991) suggests that the canyon effect is likely to have only a small, if any, affect on indoor air quality. Nitrogen dioxide measurements made by Edinburgh City Council (Edinburgh Director of Public Health) suggest that although relatively high concentrations of nitrogen dioxide do arise in some Edinburgh streets, the highest concentrations do not arise in streets where the canyon effect might be expected to be greatest. Instead the highest concentrations arise in relatively open streets, parallel to the prevailing wind, which are notorious for traffic congestion (eg St. Johns Road, Corstorphine; Ferry Road).

### 1.3 Aims of Phase 2 (The Measurement Campaigns)

The main aims of the measurement campaigns were:

i. to establish whether the canyon effect has a detectible effect on the dispersion of pollutants within narrow city streets.

ii. to establish whether the canyon effect has sufficient effect on the dispersion of pollutants in outdoor air such that it is likely that pollution levels within street canyons exceed national and international guides and limits more frequently than elsewhere in the city.

iii. to establish whether the canyon effect has a detectible effect on indoor air quality

iv. to establish whether there is a need to introduce more or less radical changes in traffic control in order to reduce the concentration of pollutants within street canyons.

Prior to undertaking any systematic measurements, some preliminary measurements were made of carbon monoxide concentrations in a number of Edinburgh streets, including North-South running street canyons. In addition, a limited number of indoor measurements were made. The aims of these preliminary measurements were to establish whether it was likely that a canyon effect would be detectible, to make a preliminary assessment of the relative importance of building geometry versus traffic behaviour in determining carbon monoxide concentrations and to give a wider context to the concentrations measured at the restricted number of sites used for the systematic measurement campaigns.

## 1.4 Pollutants

### 1.4.1 Pollutants measured

The pollution measurements made were of carbon monoxide, fine particulate matter (PM10), nitrogen dioxide, benzene, toluene and xylene. Concentrations of all these pollutants were measured in Frederick Street but only carbon monoxide and PM10 were measured in South Bridge (Fig. 3).

### 1.4.2 Sources of these pollutants within the environment

Globally, the dominant outdoor sources of carbon monoxide, benzene (and toluene and xylene) and fine particulate matter (PM10) are all anthropogenic whereas the dominant sources of nitrogen oxides ($NO_x$) including nitrogen dioxide ($NO_2$) and coarse particulate matter are natural. Natural sources of $NO_x$ include bacterial fixation of atmospheric nitrogen, volcanoes and fixation of nitrogen during electrical storms. Natural sources of particulate matter include volcanoes, sea spray and dust storms. Airborne particulate matter includes both primary particles, eg mineral dust and salts from natural sources and carbonaceous combustion products and secondary particles such as sulphates that form through reactions in the atmosphere.

The dominant anthropogenic outdoor sources of carbon monoxide and benzene (and toluene and xylene) are petrol engines and of particulate pollution and nitrogen oxides are diesel engines. Small amounts of carbon monoxide are also released into the environment from all processes involving the combustion of organic matter, for example from power stations and waste incineration. Fine particulate matter is also released from wide range of combustion processes including power stations, domestic coal burning and industrial incinerators. Oxides of nitrogen, including nitrogen dioxide, are released during the combustion of all fossil fuels and also during the manufacture of nitric acid, welding and the use of explosives. Further nitrogen dioxide forms from $NO_x$ emissions through the oxidation of nitric oxide.

There is relatively little published information about the relationship between indoor and outdoor air quality. It is clear however, that in some indoor environments, indoor sources of pollution may lead to significantly greater indoor concentrations that those prevalent outdoors. Dockery and Spengler (1981) have suggested that there is roughly a 70% penetration of outdoor particulate pollution into indoor environments that lack air conditioning.

In many indoor environments the major source of carbon monoxide, particulates, $NO_x$, benzene, toluene and xylene is tobacco smoking. The concentrations of respirable particulates can be particularly high in smoking areas such as pubs (up to 700$\mu$g m$^{-3}$, Samet et al, 1991). Carbon monoxide and $NO_x$ are also produced by gas-fired appliances. Properly fitted gas-fired central heating systems should release little carbon monoxide or $NO_x$ to the indoor environment but these pollutants are released from unvented gas fires and cookers. However, although hourly mean concentrations of carbon monoxide can rise to 40ppm in rooms where a gas cooker is in use (compared with typical indoor concentrations of 1-3ppm), there is generally little difference between the mean concentrations of carbon monoxide measured in homes that use gas cookers and those that do not (Coultas and Lambert, 1991). In contrast, Spengler et al (1983) have suggested that gas cooking adds about 25ppb to background indoor concentrations of $NO_2$ with peak concentrations reaching 400ppb (Spengler and Sexton, 1983). Traces of benzene, toluene and xylene are released from a wide range of materials including paints, solvents, cleaning materials, adhesives, correction fluid and perfumes (Wallace, 1991).

### 1.4.3 Health effects associated with measured pollutants

*Carbon monoxide:* Carbon monoxide seriously disrupts oxygen transport within the human body and at levels of exposure exceeding 28ppm over 8 hours, people with pre-existing cardiovascular problems may experience adverse affects (WHO 1979). At higher levels of exposure, exceeding 50ppm over 8 hours, neurobehavorial effects such as impaired learning ability, reduced vigilance and decreased manual dexterity are observed (WHO 1979).

*Particulate pollution:* It appears that the finest particulates, PM10, are the most hazardous to health, partly because of their ability to penetrate the respiratory system. These fine particles may also include more specific toxins such as heavy metals or polyaromatic hydrocarbons (Urban Air Review Group, 1993). The short term health effects attributed to particulate pollution include increased mortality among those with pre-existing lung and heart disease, increased respiratory illness and deficits in pulmonary function (Urban Air Review Group, 1993). Particulate air pollution may provoke asthmatic attacks in those with pre-existing asthma, but there is little evidence that asthma is caused by ambient levels of air pollution. Table 1 shows some estimates of the health effects that may arise from increases in particulate air pollution.

*Oxides of nitrogen:* Nitrogen dioxide ($NO_2$) is considered to be the most likely of the oxides of nitrogen to pose a hazard to health and acute exposure to high levels of $NO_2$ as a result of occupational accidents can result in severe lung damage (Department of Health, 1993). The lung function of normal healthy adults is unaffected by levels of $NO_2$ as high as 940ppb but epidemiological studies based on indoor air quality suggest that there is an increased prevalence of acute respiratory illness and symptoms associated with exposure to $NO_2$ concentrations of less than 2000ppb (DH, 1993). Young children, asthmatics and possibly those with chronic bronchitis or other lung disease are more susceptible to the effects of $NO_2$. About one third of asthmatics show increased bronchial responsiveness at $NO_2$ concentrations as low as 94ppb and children exposed to mean indoor concentrations of $NO_2$ of 275ppb may show an increased susceptibility to respiratory disease (DH, 1992).

*Benzene, toluene and xylene:* It is well established that exposure to benzene can lead to the development of leukaemia. There is a threefold increase in leukaemia risk at levels of cumulative occupational exposure of 40-200 ppm.years (eg. exposure over 40 years to 1 to 5ppm = 1000-5000ppb). Acute exposure to high concentrations of benzene (>25ppm) causes central nervous system depression and cardiac arrhymia. Asphyxiation and respiratory failure occur at concentrations of greater than 7500ppm (WHO, 1993).

Exposure to high concentrations (50-100ppm) of xylene and toluene may cause neurotoxic effects but these chemicals are not thought to be carcinogens (Wallace, 1991). Acute exposure to extremely high concentrations of toluene (>600ppm) causes convulsions and nausea with coma and death occurring at concentrations greater than 4000ppm (WHO, 1985).

### 1.4.4 Current environmental limits

A number of bodies have set environmental air quality standards including the Department of the Environment (DoE) and more recently EPAQS (Expert Panel for Air Quality Standards) for the DoE, the European Union and the World Health Organisation. In the absence of environmental limits for individual substances, a working environmental limit is sometimes derived from the occupational exposure limit (OEL) by dividing by a factor of 40 (or 100) to allow for lifetime rather than just occupational exposure and the presence of more vulnerable subjects in the general rather than working population (eg young children and the elderly). Some relevant environmental guides and limits are shown in Table 2.

### 1.4.5 Background levels of pollution in Edinburgh City Centre

The DoE makes continuous real time measurements of the outdoors concentration of a number of pollutants in central Edinburgh including carbon monoxide, particulate (PM10) and nitrogen dioxide concentrations in Princess Street Gardens and benzene concentrations on the roof of the medical school. Both these locations are relatively distant from traffic (35m) with respect to the measurement locations used in the canyons project but are similarly adjacent to buildings and sources of building related pollution. Table 3 summarises the DoE data for the year 1994. There is no reason to expect concentrations to have changed greatly during the last couple of years.

# 2. METHODS

## 2.1 Study Design

The study was designed to determine whether tall buildings cause detectible retardation of the dispersion of traffic pollution from streets in central Edinburgh. Systematic measurement campaigns, in which both indoor and outdoor air quality were assessed, were undertaken in two separate streets during the autumn of 1995. Previous to the systematic measurement campaigns, some preliminary measurements were made to inform the sampling strategy adopted for the systematic measurement campaigns. Measurements were made in street canyons where it was believed the greatest possible build ups in pollutant concentrations from local traffic fumes were likely to arise. Similarly, the selection of pollutants for measurement, carbon monoxide, particulates as PM10, nitrogen dioxide and selected volatile organic compounds (benzene, toluene and xylene) included only those for which the main urban source is from traffic fumes. The sampling strategy was designed to test the model illustrated in Figure 1. A combination of continuous pollution measurements (carbon monoxide) and measurements made over longer time periods (usually 24 hours) were made. This allowed the relative magnitude of any build up in pollution due to the canyon effect to assessed in relation to the variations in pollutant concentrations arising from differences in traffic flow at different times. It also gave some measure of whether the retardation of dispersion of traffic pollution from street canyons could give rise to much greater short term peaks of pollutant concentrations in canyons than elsewhere in the city. Similarly it was possible to determine, whether longer term mean concentrations of pollutants are greater in street canyons than elsewhere in the city.

## 2.2 Preliminary Investigations

Prior to making a systematic investigation of the canyon effect, some instantaneous measurements were made of carbon monoxide pollution at street level outdoors, indoors in a tenement flat and in a moving vehicle during the early summer. These initial measurements were made with a hand held Neotox personal carbon monoxide monitor which reads in ppm but has a much lower sensitivity than the detectors used for the systematic measurement campaigns.

## 2.3 Selection of Locations and Sampling Strategy for Systematic Measurement Campaigns

The sampling strategy developed for the systematic measurement campaigns was designed to test the results of the laboratory simulations described in the literature review and illustrated in Figure 1. In order to assess whether the canyon effect is of sufficient magnitude to be of concern, the measurement locations were selected to be in streets where canyon effect was likely to be maximised by building geometry and where the traffic flow (and therefore the generation of traffic pollution) appeared to be relatively high in comparison to other city streets. Candidate streets were those that are perpendicular to the prevailing West wind, are lined by buildings that are at least three storeys high and are major traffic routes. Relatively few of the major traffic routes in Edinburgh run North-South and within these streets, there are only short stretches that might be described as street canyons. A further constraint was that we needed daily access to our instruments in order to undertake the measurements which required a high degree of co-operation from property owners. Given that the primary concern of The Scottish Office was related to residents of the city's traditional tenement blocks, measurements would have ideally been made in streets where there is a high residential population but this was prevented by logistical difficulties. Although press articles generated a lot of interest from individuals in the city (Appendix 2), few of these individuals lived in streets with a North-South orientation and a high traffic flow. Even targeted mail shots did not produce the clusters of volunteers that would have been required to test the canyon model.

The two streets eventually selected for the measurement campaigns were South Bridge (NGR: NT26027335) and Frederick Street (NGR: NT25157393) (Fig. 3). The buildings selected were business rather than residential properties because of the logistical advantages of having easy access from Monday to Friday each week at pre-agreed times of day. Also for logistic reasons, the buildings were, as far as possible, selected to have single rather than multiple occupants.

The planned outdoor sampling strategy at each of the measurement locations was designed to sample the zone where the canyon model predicts the highest concentrations of traffic pollution should arise, that is, close to street level, mid block on the sheltered (West) side of the street (Fig. 1). Additional measurements were made directly opposite, on the other side of the road and at various levels above the street, in order to test whether the difference in concentrations between locations was compatible with a canyon model. The actual outside sampling strategy finally adopted was limited by practicalities: the University only allowed the IOM access to a ground floor cellar in South Bridge, rather than the top floor office that had been initially proposed in early discussions with the University. Similarly it would have been very difficult make measurements at ground floor level for any of the business premises without breaching their security systems.

Indoor measurements were made in parallel with the outdoor measurements, in order to compare indoor and outdoor concentrations of pollutants in each of six situations: small office, small staffroom, large open plan office, large unused open plan office, poorly ventilated, unheated cellar and poorly ventilated, unoccupied attic flat.

## 2.4 Measurement Locations

### 2.4.1 South Bridge

*James Thins Booksellers:* James Thins occupy most of the block between Infirmary Street and Drummond Street on the East side of South Bridge. The sampling sites were about halfway between two side streets (about 30m from either street corner), directly opposite the entrance to Old College (Edinburgh University). Measurements were made below windows outside the first, second and third (attic) floor levels and also inside the second floor office from which the outside samples were collected. This gave good coverage of the vertical variation in concentrations of pollutants above South Bridge. Unfortunately the power supply at James Thins is switched off at night (from 2200 to 0600 hours approximately) and so there is no carbon monoxide data for these periods. The mains powered pumps that were initially used to collect particulate samples were subsequently checked to ensure that their internal batteries would have charged sufficiently while the mains was on, to have run satisfactorily during the periods when the power was off. During the final days of the monitoring campaign the mains supplied pumps were replaced with pumps supplied by car batteries.

James Thins is heated by a gas-fired central heating system that uses water-filled radiators and there is no smoking in the office in which pollution measurements were made. The windows of the office are traditional wooden sash windows rather than modern sealed units. The pipes and cables to the equipment placed outside of the office were passed through the open window. Foam pads held in place with weather proof tape were used a draft excluder.

*Old College (Edinburgh University):* Old College is on the West side of South Bridge and occupies the block between Chambers Street and South College Street. Measurements were made in a cellar within the main gate to Old College, which is halfway between Chambers Street and South College Street (about 40m from either street corner). The main gate of Old College comprises a central archway for traffic and smaller archways to either side for pedestrians. The cellar occupies the interior of a tower between the main archway and the Southern smaller arch. The floor of the cellar was about 1m above street level, the window through which the sampling devices were fed to the outside was about 2.5m above street level (overlooking the street). The height of the cellar was of the order of 8m (there are no dividing floors within the gatehouse towers). (There are no dividing floors within the gatehouse tower). Sampling devices were attached immediately outside the window, inside the cellar at about 1.5m above the floor and at floor level. The cellar is unused and unheated and the window was left open throughout the sampling period.

### 2.4.2 Frederick Street

The measurements were made at first and third floor level, inside and outside, on both sides of Frederick Street, from windows almost halfway between George Street and Rose Street (about 20m from the intersection with George Street).

The rooms used on the East (Sun Alliance) side of the road are large open plan offices. That on the first floor was in use and, on most working days, a high proportion of the windows were open. The third floor office was unused and the only open window was the partially open window through which our sampling tubes were passed. Sun Alliance have a no-smoking policy within their offices.

The rooms used on the West (Woolwich Building Society) side of the road were the first floor staff room used mainly over the lunch time period and a third floor room in an unoccupied attic flat which is entirely unused and unheated. No smoking is allowed within the Woolwich Building which is heated by gas central heating. The windows in both the staff room and the attic flat are traditional wooden sash windows. Those in the staff room was closed during the sampling period and the pipes and cables to the outside equipment were passed through a purpose drilled hole in the window frame. The window in the attic was left open throughout the sampling period.

## 2.5 Measurements made during the Systematic Sampling Campaigns

### 2.5.1 Carbon monoxide

Continuous real time measurements of carbon monoxide concentrations were made with Analox 3000S Carbon Monoxide Sensors (0-100ppm) supplied by Scottish Anglo. The manufacturers claim a sensitivity of 0.1ppm but a value of 0.2 or 0.3ppm is probably more realistic. Two sets of four sensors were used which allowed simultaneous measurement of carbon monoxide concentrations at four locations on each side of the study streets. Each set of four sensors supplied information as electrical signals in mA to a central unit (Analox 1300 surveyors) which in turn passed the information to a logging device (Grant 1000 Series Squirrel). The logging device was downloaded onto a computer each day. The sensors could operate remotely at distances of up to 1000m, although the maximum cable distances used were of the order of 20m.

The handbook supplied with the sensors provided a formula for the conversion of the current readings in mA to concentrations of carbon monoxide in ppm. This was tested before the sensors were employed in the first measurement campaign by undertaking a preliminary calibration exercise with the sensors wired up with the 2m lengths of cable they were supplied with. A second laboratory calibration was performed at the end of the second measurement campaign, with the sensors wired up with the longer lengths of cable used during the measurement campaigns. When the sensors were wired up with these longer lengths of cable it was found to be necessary to add an additional correction factor to the expression used to convert current in mA to concentration of carbon monoxide in ppm.

### 2.5.2 Particulates (PM10)

Daily mean values of PM10 concentrations were measured by collecting samples on glass fibre filters using a modified personal sampler (Aitkin and Donaldson 1995). In its use as a personal sampler, this device samples the thoracic fraction (CEN, 1992) of airborne particulate matter which is similar to PM10 any differences arising from the change of usage of the sampler, from personal to static were not considered to be significant for particle sizes less than 10$\mu$m. Flow rates were set at 2 litre/ minute (in order that size selection should be as close as possible to PM10) and checked at both ends of each sampling period. The filters were analysed gravimetrically following the methods described in MDHS14. Many samples had masses close to the detection limit of the method (about 30$\mu$g, equivalent to 10$\mu m^{-3}$) and it was hoped to use the reflectivity of the filters to give us a semi-quantitative measure of diesel soot concentrations (all the filters are discoloured regardless of whether a measurable mass of dust is present). Although the filters did give a range of reflectance values which reflected different degrees of coloration, there was no obvious relationship between reflectivity and the gravimetric mass of dust on filter.

A large number of the PM10 samples were lost because of wet windy weather which blew water into the sample heads. The pumps then failed because of the excessive dampness. The glass fibre filters became sticky with the smallest degree of dampness and a large number of the filters were damaged in getting them in and out of the samplers. The damage to filters reduced their mass which made the detection of very small masses of particulate pollution difficult. It is not clear why the incidence of damaged filters was so high as both the samplers and the filters have been widely used in previous IOM studies. If a future study of environmental dust levels were also to utilise IOM personal samplers, it would be advisable to use membrane rather than glass fibre filters and to improve the weather protection for the sampling head. It would however be difficult to eliminate the possibility of water penetrating the sampling head and still sample outside air.

### 2.5.3 Nitrogen dioxide

A known volume of air was drawn through triethanolamine impregnated glass fibre filters over each sampling period (usually 24 hours). Flow rates were set at 1 litre/minute and checked at both ends of each sampling period. The filters were then extracted with triethanolamine solution and the resulting solutions treated with hydrogen peroxide, sulphanilamide and N-(1-naphthyl) ethylene diamine dihydrochloride. The $NO_2$ reacted to form a purple colour, the intensity of which was measured spectrophotometrically to determine the mass of $NO_2$ collected on each filter (NIOSH, 1978). The sensitivity of the method was 0.2$\mu$g per sample.

### 2.5.4 Benzene, toluene, xylene

A known volume of air was drawn through tubes containing activated charcoal over each sampling period (usually 24 hours). Flow rates were set at 0.2 litre/minute and checked at both ends of each sampling period. The charcoal was then desorbed in carbon disulphide and an aliquot analysed by gas chromatography with flame ionization detection (HSE 1987). The sensitivity of the method was 0.1$\mu$g benzene, toluene and xylene per sample.

### 2.5.5 Quality assurance

The gravimetric analysis of samples to determine concentrations of PM10 was undertaken to the standards outlined within the relevant IOM NAMAS quality systems. The analysis of samples for nitrogen dioxide and the solvents, benzene, toluene and xylene, was undertaken to similar quality standards which include rigorous calibration procedures, the routine analysis of blank samples, regular 10% checks of analytical results and rigorous procedures for checking the accuracy of data entry to the databases used to calculate and analyse the concentration data.

## 2.6 Weather Data

Selected weather data for Edinburgh Airport (10km to the West of the city centre) for the period covered by the measurement campaigns was purchased from the Meteorological Office. This data includes hourly windspeed and direction, hourly rainfall, hourly Pasquill stability index and daily maximum and minimum temperatures. The Pasquill stability index is a measure of turbulence based on an ordinal seven point scale, ranging from 1 = very unstable to 7 = very stable. The wind speed and direction are 10 minute means at each time of observation on the hour. Rainfall is total rain in the preceding hour. The Pasquill stability index is based on prevailing conditions in the preceding hour.

## 2.7 Data Processing and Analysis

The carbon monoxide measurement data from the loggers were downloaded as a series of one and two minute readings of current (mA) for each monitor. After calibration these measurements were averaged to form hourly mean concentrations of carbon monoxide. The meteorological data was linked to the hourly carbon monoxide averages so that the hours over which the measurements were averaged corresponded to the hours over which the weather data was reported. The wind speed and direction were snapshot measurements taken at the commencement of the corresponding hours over which carbon monoxide was averaged. The South Bridge campaign (19th September to 12th October), but not the Frederick Street campaign (23th October to 10th November), fell within British Summer Time. Since the hour of the day is used as a surrogate variable for the rate of traffic flow in the analysis of hourly carbon monoxide levels, the hour of the day used in each campaign corresponded to actual clock-time, BST or GMT, during each campaign.

The hourly carbon monoxide data were described using a number of plots, the most basic of which are time series plots of hourly levels during each campaign at each location. The exploratory analysis of the effect of street canyon geometry involved the comparison of carbon monoxide levels at the different outdoor locations within a street at each point in time, taking account of wind speed and direction. Where wind direction has been incorporated, it has generally been categorised into broad direction categories which reflect the prevailing wind direction at the time in relation to the direction of the street. Hours when no wind was recorded have no specific wind direction and zero hours of wind speed have been categorised separately. Indoor and outdoor levels were compared graphically at each location where both series of measurements had been recorded to investigate the relative effects of possible outdoor sources on indoor concentrations.

Apart from carbon monoxide all the other pollutants were measured over 24 hour periods (weekdays) or 72 hour periods (weekends) and so the hourly carbon monoxide measurements were further averaged to form means over identical periods. Due to incomplete sampling, not all of these means cover entirely the periods to which they refer. To allow weather conditions to be related to these daily pollutant levels, the weather data was also summarised over the 24 hour and 72 hour periods. For wind speed the mean speed was reported while for wind direction the trigonometric mean direction was used. Total rainfall was cumulated over each period and for the Pasquill stability index, the median score was chosen as an appropriate summary. As with the hourly carbon monoxide measurements, the daily measured pollutants were also analysed graphically to explore the effect of street canyon geometry and to compare indoor and outdoor levels. Additionally, the relationship between pairs of pollutants was analysed graphically to provide information on possible sources, expected in the main to be petrol and diesel engines.

## 2.8 Street Geometry and Traffic Behaviour in South Bridge and Frederick Street

A number of features of street geometry might affect the dispersion of traffic pollution including orientation, aspect ratio, relative building heights, the presence of breaks between and within buildings and features that affect traffic flow like gradient, traffic lights, pedestrian crossings. Other features of the measurement locations that are likely to have affected air quality during the measurement campaigns are patterns of traffic flow, vehicle mix and the presence of any significant sources of pollution, other than traffic (for example flues from central heating systems).

### 2.8.1 Street geometry

Although, the monitoring locations in South Bridge and Frederick Street were sited as far from street intersections as possible, the distances involved are not very great (20-40m, compared with a street width of 15m). Even when cloud movements suggested that the dominant airflow above rooftop level was perpendicular to these streets, at pavement level, there was usually a significant, intermittent breeze along their length.

Both streets have an uneven sky line and the buildings in neither street extend as far back as the next parallel street (which contrasts with the solid blocks used in the model simulations, Fig. 2). The canyon wall on the West side of South Bridge (the University) is broken by a gateway into the central courtyard of Old College, so that the street is not as sheltered from the prevailing West wind as suggested by street maps.

### 2.8.2 Traffic

Both South Bridge and Frederick Street appear to be congested with traffic through much of the working day and during the evening. Observation during the sampling periods suggest that there may be a mid morning lull in traffic flow at both locations. Sundays are noticeably quieter in South Bridge than other days, whereas Frederick Street appears to be busy on all days of the week. South Bridge is a major arterial road and one of the busiest bus routes in Edinburgh. The traffic includes a much higher ratio of buses relative to private cars than would be typical of other city streets, except Princes Street. South Bridge is heavily used by people travelling to the city centre, both to work during the day and for leisure activities in the evening. South Bridge is also close to the Festival Theatre and a large number of pubs and restaurants. Frederick Street is in the city centre and not itself an arterial road or a major bus route, although the traffic does include buses. A high proportion of the traffic that uses Frederick Street is related to tourism and people shopping or eating in the city centre.

The presence of traffic control measures in both South Bridge and Frederick Street meant that neither site was ideal for testing the canyon effect because of the resultant unevenness of pollutant source within each canyon (Fig. 4). In South Bridge, the traffic lights and pedestrian crossing at the intersection of South Bridge and Chamber Street lead to traffic queues forming on the West side of the road that extend back past the University cellar. In contrast traffic rarely queues outside James Thins as the next pedestrian crossing to the South, is about 150m away. In Frederick Street traffic queues on the West side of the road, outside the Woolwich, waiting to gain access to the mini roundabout at the intersection of Frederick Street and George Street. On the East side of Frederick Street, outside the Sun Alliance building, traffic queues at the pedestrian crossing where Rose Street intersects Frederick Street (Fig. 4). In general the traffic is more likely to tail back past the Woolwich on the West side of the road than past the Sun Alliance, because of the relative distance of each building from the cause of a tail back. However, during periods when Princes Street is particularly congested, severe congestion also arises along the entire length of the East side of Frederick Street.

# 3. RESULTS OF MEASUREMENT CAMPAIGNS

## 3.1 Results of Preliminary Investigations

A number of preliminary measurements of instaneous carbon monoxide concentrations were made in central Edinburgh during the period of late May to early June 1995. The measurements were made with a single hand-held monitoring device. Consequently the summary of the results of these measurements outlined below is based on a number of series of successive readings at different localities, each reading being separated by a few minutes in time, rather than being based on simultaneous measurements as were used for the systematic measurement campaigns.

Some preliminary measurements of instaneous carbon monoxide concentrations were made at the Southern end of South Clerk Street (Fig. 3) during a number of evenings in late May and early June, when overhead cloud movement suggested a Westerly wind (it was not cost effective to obtain the weather data for what was only a very preliminary examination of carbon monoxide concentrations in central Edinburgh). These measurements suggested that concentrations of carbon monoxide were slightly lower at the intersection of South Clerk Street and East and West Preston Street than on the pavement mid-block (Fig. 5) and slightly higher on the West side of the street than the East (Fig. 5). Concentrations were also relatively high on the corner between Lutton Place and South Clerk Street (Fig. 5). Concentrations on the backgreen at 71 South Clerk Street (East side) were consistently slightly lower than in the street (Fig. 5). Traffic flow in South Clerk Street is still quite high during the evening and vehicle movement in both directions is sluggish due to the lights at the intersection with Preston Street and at the Pedestrian crossing immediately South of Lutton Place. Traffic also queues at the exit of Lutton Place.

Further instaneous measurements of carbon monoxide concentrations were during the morning rush hour along the East side of the Dalkeith Road between the University Nursery and the Commonwealth Pool (Fig. 3) on days when wind overhead was from the West. These measurements suggested that relatively small topographic features may have a marked effect on the dispersion of traffic pollution (Southbound traffic flows fairly freely along this section of road during the morning, so there was no complicating effect of stationary traffic). The University Nursery is set back from the road and typical concentrations of carbon monoxide at the pavement were about 2ppm. The pavement from the Nursery to outside the Pool is bounded by 2m high wall to the East and, from a few tens of metres North of the nursery to a few tens of metres South of the Pool, pavement concentrations of carbon monoxide were of the order of 4 to 6ppm (1-3ppm at gateways). Outside the Pool concentrations were about 3ppm, but significantly higher adjacent to the intersection with Holyrood Park Road (Fig. 3).

Other measurements made at various locations in central Edinburgh indicate that relatively high concentrations of carbon monoxide built up at street corners where traffic was queuing at traffic lights. For example, at lunchtime on a warm still day in late May (23/5/95), concentrations of carbon monoxide at the intersection of South Bridge with the High Street (Fig. 3) were 9ppm as opposed to 4 to 5ppm on the East side of South Bridge and 2 to 3ppm in South Clerk Street. The highest outdoor concentrations recorded (15ppm) were measured during the rush hour on a number of mornings in late May-early June at the intersection of Dalkeith Road and Holyrood Park Road (outside the Commonwealth Pool), despite the open, exposed nature of the corner which might be expected to lead to enhanced dispersion of traffic pollution. Other measurements made suggested that relatively high concentrations of carbon monoxide can also arise in locations where there is no obvious link with traffic. For example, concentrations during the morning rush hour during late May-early June, at the intersection of East Cross Causeway and St. Leonards Street (Fig. 3) were consistently higher than those measured anywhere else along St. Leonards Street (for example 14ppm compared with 4ppm ten metres further North along the West side of St. Leonards Street).

A limited number of indoor measurements (3rd floor flat on East side of South Clerk Street, facing onto back green) suggested that carbon monoxide concentrations in the living room were similar to those outside (0-2ppm) but concentrations in the kitchen were higher than outdoors when the gas cooker was in use. A further limited number of measurements suggested that carbon monoxide concentrations within a moving vehicle (1.1 Fiesta with a petrol engine) are much higher than those prevalent outside of the vehicle. Concentrations within the vehicle rose to more than 10ppm and as high as 20ppm when the vehicle was stationary at lights or a roundabout and were stable at about 7ppm during travel at about 50mph on an open road.

## 3.2 First Systematic Measurement Campaign: South Bridge (late September - early October 1995)

### 3.2.1 Weather during sampling period

The period, 19th September to 12 October, over which pollution measurements were made was generally very breezy (mean 9.5 knots (=17.6km/hour), range 0-22 knots (= 49km/hour); Fig. 6) with periods of heavy, but rarely very continuous rain (maximum hourly rainfall 3.8mm, maximum daily 7.2mm, mean daily 1.4mm). Winds were generally from the West and South (modal direction 210; Fig. 7). Winds from the East and Northeast were generally very light and prevailed over intervals of much less than half a day. Windspeeds were generally greatest when winds were from the Southwest. The hourly values of Pasqill Stability Index ranged from 2 to 6 (moderately unstable to moderately stable), but for most of the sampling periods, stability was neutral throughout the day at 4 (Fig. 8). Temperatures were typical for the time of year with daily maxima ranging from 13.1-19.1°C and minima ranging from 0.9 to 11.7°C.

### 3.2.2 Carbon monoxide data

The hourly mean concentrations of carbon monoxide measured ranged from 0.9-11.4ppm and daily mean concentrations ranged from 1.3-6.2ppm (Table 4). As no night time measurements of concentrations were made on the East side of the road, the mean values for each sampling period are probably higher than the true daily mean values. The 11.4ppm measurement was made on Tuesday 23rd September (Fig. 9) which appears to have been a day during which carbon monoxide concentrations were very much higher than during any other time during the measurement period. It is not known why the concentrations were so much higher on that day, compared with other days. Given that the concentrations appear to be very atypical, the data for the 23rd September have been omitted from Figures 10-18. In general the outdoor concentrations of carbon monoxide measured on the West side of the road, outside the University cellar, were greater than those measured on the East side of the road outside James Thins, particularly during periods when the wind was from the West (Fig. 10). During the short periods when the wind was from the East, concentrations appear to have been higher on the East side of the street (Fig. 10). The difference between the two sides of the road was also greatest during the periods when overall concentrations of carbon monoxide were greatest (Fig. 10). The concentrations measured at first floor level on the East side of the road were greater than those measured at second and third floor (Figs. 10 and 11). The concentration difference was greatest when overall concentrations were highest. The concentrations measured at third floor level tended to be slightly greater than those measured at second floor level, the differences between the two sets of readings are generally less than the probable sensitivity of the carbon monoxide monitor. The most marked peaks in carbon monoxide concentrations arose at first floor level (Fig. 9) and the diurnal variation in carbon monoxide concentration was least at third floor level (Fig. 9).

The outdoor concentrations of carbon monoxide in South Bridge appear to show a relationship with windspeed provided some account is taken of differences in the volume of carbon monoxide generated by traffic during different periods in the day (Fig. 12). If, for example, only rush hour (0700-0900 and 1600-1800) concentrations are considered, then it is apparent that the greatest concentrations arise under conditions of little, but not no, wind and the lowest concentrations at the greatest windspeeds recorded (Fig. 12). The difference in carbon monoxide concentration between the two sides of the road shows no consistent relationship with windspeed, even if only rush hour concentrations are considered (Fig. 13). There appears to be no relationship between outdoor carbon monoxide concentrations and rainfall. It is difficult to determine any relationship between carbon monoxide concentrations and stability index as stability was virtually constant at 4 (ie neutral) during the measurement period.

There was a marked diurnal variation in outdoor carbon monoxide concentrations on both sides of South Bridge with much lower concentration measured at night (2300-0700) that during the day (Figs 9 and 14). There were also marked weekday peaks in measured daytime concentrations between 0700 and 1000 and between 1500 and 1800 (Fig. 14). On about half of the measurement days there was an additional mid-evening peak of concentration at about 1900. On Saturdays, there was no marked peak in carbon monoxide concentrations in the morning, the late afternoon peak was about an hour earlier than on weekdays and the evening peak of concentration was much greater than on other days. On Sundays, carbon monoxide concentrations were lower than those measured on weekdays (Fig. 9). There was no early morning or late afternoon peak in carbon monoxide concentrations but there was a mid evening peak (Fig. 9). The day time peaks in concentration between 0700 and 0900 and between 1600 and 1700 are much less marked than on the East side of the road. The most marked mid-evening peak in concentration was measured on a Saturday (Fig. 9).

The concentrations of carbon monoxide measured in the second floor office in Thins were slightly higher than those outside, but show a similar pattern of hour by hour variation (Fig. 15). Peak hourly concentrations tended to be slightly higher outdoors than indoors (Fig. 15) and the highest hourly mean concentrations measured outdoors did not coincide with the highest hourly mean concentrations measured indoors (Fig. 15). The concentrations of carbon monoxide were slightly lower inside the University cellar than those measured outside (Figs 15, 16). The data show a very similar pattern of variation through time, but the peaks in hourly mean concentration were less marked inside than outside (Figs 15, 16).

The air quality standard set by the UK Expert Panel on Air Quality Standards (EPAQS, 1994) for carbon monoxide (8 hour mean of 10ppm) was not exceeded at any of the measurement localities in South Bridge during the measurement period. The daily mean outdoor concentrations of carbon monoxide are generally slightly higher than the highest daily mean concentration of carbon monoxide measured for the Department of the Environment (DoE) in Princess Street Gardens during 1994 (2.1ppm).

### 3.2.3 Particulate (PM10) concentrations

The measurements of daily mean outdoor concentrations of PM10 ranged from 4.0 to 135.5$\mu gm^{-3}$. These measurements may underestimate the true concentration of fine particulates as most of the errors in measurement would have resulted from damage to the glass fibre filters. The outdoor concentrations of PM10 were much greater on the West side of the street outside the University, than on the East side of the street but there was no consistent relationship between the outdoor concentrations measured at different levels above the street (Table 5, Fig. 17). Particulate concentrations were lowest at weekends and higher during the intervening working weeks (Table 5).

Indoor particulate concentrations ranged from 3.4 to 51.9$\mu gm^{-3}$ and were fairly similar in both the University cellar and the second floor office in Thins. There is no clear relationship between indoor and outdoor concentrations of PM10 (Fig. 18). Concentrations in the office in Thins were generally higher than those outdoors whereas those in the University cellar were generally lower than those outdoors. Particularly high outdoor concentrations of PM10 do not appear to have been paralleled by higher than normal indoor concentrations (Fig. 18).

The PM10 concentrations measured in South Bridge are generally higher than those measured in Princes Street Gardens during 1994 with some measurements being more than double the maximum daily mean concentration measured in Princes Street Gardens 62$\mu gm^{-3}$. Particulate concentrations exceeded the EPAQS (1995) guidelines on a number of occasions (Table 4).

## 3.3 Second Systematic Monitoring Campaign: Frederick Street (late October - November 1995)

### 3.3.1 Weather during sampling period

The weather was very variable during the sampling period, from 23rd October to 10th November. The first five days were wet and windy with daily mean windspeeds ranging from 9.4 to 17.1 knots (17.0 to 31.7 km/hour) and maximum windspeeds of 30 knots (55.6km/hour; Fig. 19). Winds during this period were from the South and West (modal direction 240; Fig. 20). The maximum hourly rainfall was 3.8mm and maximum daily rainfall 26.4mm. The median stability index was 4. Subsequently the weather was much less windy with daily mean windspeeds ranging from 1.5 to 9.0 knots (2.8-16.7km/hour) and periods of no wind. Winds were generally from the West (modal direction 240), light but variable, with Easterly winds occasionally prevailing for periods of up to 12 hours. Daily median Pasquill Stability values ranged from 4 to 6, ie. neutral to stable (Fig. 21). Temperatures during the sampling period were generally quite mild for mid autumn, although there were four nights on which temperatures dropped below zero and a further four nights when temperatures dropped to between 0 and 1°C, cold enough to give a frost. Daytime maxima ranged from 9.2 to 19.7°C.

### 3.3.2 Carbon monoxide data

The outdoor concentrations of carbon monoxide on both sides of Frederick Street were both generally higher and more variable at first floor level than at third floor level (Figs 22, 23; Table 6). Concentrations of carbon monoxide were also generally higher on the West side of the road than on the East, particularly at the first floor level and when the wind was from the West (Fig. 24). There was less difference between the two sides of the road during periods when there was little or no wind and during periods when the wind was from the East, concentrations were generally higher on the East than on the West side of the road (Fig. 24). There was generally a much greater difference in carbon monoxide concentrations with height above the street on the West side of the road (Woolwich) than on the East (Fig. 23).

The highest outdoor concentrations of carbon monoxide were measured when windspeeds were low rather than during periods of no wind. As with the South Bridge data, there is a relationship between carbon monoxide concentrations and windspeed during periods when the generation of carbon monoxide within the street was fairly constant, eg. at night or during the rush hour. If data from the rush hour periods is considered (0700-0900 and 1600-1800) there is a strong relationship between carbon monoxide concentration and windspeed with minimum concentrations arising during periods of high windspeeds and maximum concentrations during periods of low windspeeds (Fig. 25). There is no relationship between measured carbon monoxide concentrations and rainfall. A weak relationship with stability index simply reflects the prevalence of more stable conditions during periods of little or no wind and less stable conditions during particularly windy weather.

The magnitude of the differences in concentration between the two sides of the road and between first floor and third floor levels, during periods when the wind was from the West, appear to be related to windspeed when all data points are considered (Fig. 26). However, if only the data from the rush hour periods is considered, there is a clear trend for the differences between the two sides of the street and at different levels above the street to be greatest at low windspeeds and least at relatively high windspeeds (Fig. 26). The differences under conditions of no wind are slightly less than if there is a very slight breeze (Fig. 26).

There is a marked hour by hour variability in outdoor carbon monoxide concentrations in Frederick Street (Fig. 27). The concentrations of carbon monoxide measured between 0800 and 2300 were significantly greater than during the night time period. On working days peak hourly mean concentrations carbon monoxide generally arose between 0800 and 1000 and again between 1700 and 1800. At the weekend peak hourly concentrations arose between 0900 and 1100, 1600-1700 and 1900-2100. The weekend morning peak in hourly concentrations is much greater on the East side of Frederick Street, than the West. Concentrations of carbon monoxide over weekends were not significantly lower than those measured on working days and there appears to have been little difference between Saturdays and Sundays in either diurnal variation or in overall concentrations of carbon monoxide. The diurnal variation in outdoor carbon monoxide concentrations was least marked on the windiest days.

The relationship between indoor and outdoor concentrations of carbon monoxide in Frederick Street appears to have varied according to how efficiently the rooms used for measurements were ventilated. In Sun Alliance offices, where the windows were permanently open there was little difference between the readings on the indoor and outdoor monitors (Fig. 28). The concentrations inside the first floor office appear to have been slightly greater than those immediately outside, particularly when the outside readings were less than 2ppm (Fig. 28) In the Woolwich staff room, where the indoor monitor was isolated from the outdoor monitor by a closed window, the outside concentrations of carbon monoxide were generally greater than those inside (Fig. 28). The diurnal variation of concentrations in the staffroom was out of phase with the outside diurnal variation (Fig. 29) with a sharp morning rise in concentrations occurring about 2 hours later than outdoors. This rise in concentration is not followed by the daytime trough observed outside and maximum concentrations are reached at about 1900, about 2 hours later than outside.

The air quality standard set by EPAQS (1994) for carbon monoxide (8 hour mean of 10ppm) was not exceeded at any of the measurement localities in Frederick during the measurement period. The daily mean outdoor concentrations of carbon monoxide are generally similar to or higher than the highest daily mean concentration of carbon monoxide measured for the Department of the Environment (DoE) in Princess Street Gardens during 1994 (2.1ppm).

### 3.3.3 Particulate (PM10) concentrations

There are too few PM10 data to determine whether there were consistent differences in dust concentrations between the various measurement locations (Table 7, Fig. 30). The data suggest that outdoor dust concentrations were slightly higher at first floor level than at third floor level on both sides of Frederick Street and higher on the East (Sun Alliance) side of the road than the more sheltered West side of the road (Table 7). The dust concentrations measured outdoors were generally greater than those measured indoors (Fig. 31). There appears to have little difference in dust concentrations between the working week and weekends (Table 7).

There are also too few data to determine whether dust concentrations were affected by wind direction, wind speed or rainfall.

The measured particulate concentrations are generally higher than those measured in Princess Street Gardens during 1994 (annual mean - $20\mu gm^{-3}$). The measured concentrations of PM10 also exceeded the guideline of $50\mu g\ m^{-3}$ proposed by EPAQS (1995) on a number of days (this guideline is however much tighter than previously suggested environmental limits).

### 3.3.4 Volatile organic compounds

During most of the sampling period outdoor concentrations of benzene, toluene and xylene were highest outside the first floor of the Woolwich and generally lowest outside the third floor of Sun Alliance (Tables 8 and 9). On days when the wind was dominantly from the West, benzene, toluene and xylene concentrations outside the first floor of the Woolwich Building Society were generally higher than outside the first floor of the Sun Alliance whereas outdoor benzene concentrations at third floor level were about the same on both sides of the road (Figs 32, 33, 34). Outdoor xylene and toluene concentrations at third floor level were generally greater on the West (Woolwich) side of the road than on the East (Figs 32, 33, 34). Outdoor concentrations of benzene and xylene on the East (Sun Alliance) side of the road and of xylene on the West side of the road were generally greater at first floor than at third floor level (Figs. 32, 34). There was no consistent difference in outdoor benzene and toluene concentrations at first and third floor level on the West side of the road (Figs 32, 34). The highest outdoor concentrations of all three compounds arose under conditions of low windspeed and no rainfall, although there are too few data to show a consistent relationship between measured concentrations and the windspeed and rainfall data (Figs 35, 36). There was no consistent difference in the measured concentrations of any of the three compounds between working days and weekends.

In general terms the indoor concentrations of benzene and xylene were similar to the outdoor concentrations of these substances at all four localities whereas the indoor concentration of toluene in the Woolwich staffroom was very much greater than that measured outdoors (Tables 8, 9; Fig. 37). The data suggest a common source for most of the outdoor benzene, toluene and xylene pollution (Fig. 38) but the dominant source of these chemicals within the Woolwich staffroom was however characterised by a much higher toluene to benzene or xylene ratio than the outdoor source (Fig. 38).

There was no exceedence of the 5ppb limit set by EPAQS (1995) for environmental benzene. There are no comparable guides or limits for xylene or toluene, but occupational exposure limits for both these substances are much higher than that for benzene. The mean concentrations of benzene were somewhat higher than the 0.7ppb 1994 annual mean but less than the 3.7ppb maximum daily mean measured on top of the Medical School for the DoE.

### 3.3.5 Nitrogen dioxide

The approximate daily mean concentrations of nitrogen dioxide measured outside ranged from 2.5 to 41.5ppb and inside from 6.8 to 41.5ppb (Table 10). In comparison, the annual mean concentration of nitrogen dioxide ($NO_2$) measured in Princes Street Gardens is 27ppb with a maximum daily mean of 53ppb (1994). There appears to have been no marked difference in $NO_2$ concentrations between working days and weekends.

Concentrations were generally higher on the east side of the road (Sun Alliance) than on the west side at both first floor and third floor level (Fig. 39). There are no consistent differences between the concentrations measured at first floor level and at third floor level on either side of the road. The highest outdoor concentrations of $NO_2$ arose under conditions of low windspeed and little or no rainfall (Fig. 40).

The data do not show a consistent relationship between indoor and outdoor concentrations of nitrogen dioxide, although there is generally less difference between the indoor and outdoor concentrations at each location than that between indoor or outdoor concentrations at different locations (Fig. 41).

## 3.4 Relationships Between Measured Pollutants

Scatter plots of pollutant concentrations measured in Frederick Street suggest that there is no clear relationship between particulate and nitrogen dioxide concentrations at any of the measurement localities (Fig. 42). There are clear relationships between benzene and carbon monoxide concentrations and toluene and carbon monoxide concentrations on the East side of the road with both benzene and toluene concentrations showing a positive co-variation with carbon monoxide. Similar relationships are not however apparent on the West side of Frederick Street (Fig. 43).

# 4. DISCUSSION

## 4.1 General Considerations

The outdoor concentrations of traffic pollution in city streets are governed by traffic flow, vehicle mix, weather conditions and street geometry. The main aim of this discussion is to assess whether street geometry, ie the "canyon effect", is as important as other factors in governing outdoor air quality in the streets of Scottish cities. This includes not only an assessment of the relative importance of the factors governing the concentrations of traffic pollution in streets, but also the relative importance of traffic pollution generated within the individual streets as opposed to pollution from other sources (eg buildings, background traffic pollution) in determining local air quality. As noted above, indoor air quality is likely to be significantly affected by indoor sources of air pollution, but the data do allow some limited assessment of the relationship between indoor and outdoor air quality. Given the nature of the selected monitoring sites, it is not possible to make any general assessment of probable air quality in domestic premises, where the sources of indoor pollution (eg gas cookers, gas fires, smoking) are likely to be much greater than in any of the premises in which measurements have been made.

The geometry of Edinburgh streets deviates significantly from the idealised model canyons used in the model simulations (described in Appendix 1). The effects of the uneven skyline in both South Bridge and Frederick Street and of the presence of open space behind buildings facing each street, may be to increase the turbulence of airflow across the top of, and therefore within both streets. This might be expected to lead to more efficient dispersion than predicted by the model. The short ratio of block length to street width, and the presence of breaks in the canyon walls such as the entrance to Old College might be similarly expected to increase airflow and therefore dispersion within the street.

The spatial pattern of generation of traffic pollution in both South Bridge and Frederick Street also deviates significantly from that used in laboratory simulations (above). In particular, the prevalence of queuing traffic on the West side of the road rather than the East, at both localities, would have lead to a greater source of pollutants on the West rather than the East side of the road. This complicates the assessment of the magnitude of any canyon effect as the model predicts that dispersion should also be least effective from the sheltered West side of the road.

The breezy weather conditions that prevailed during the South Bridge sampling campaign probably prevented the build up of pollutants that might arise during calmer, more settled weather. The prevalence of Westerly winds during this period also limited the extent to which the relative importance of probable differences in source on either side of the street and of the "canyon effect" could be assessed. The more varied weather conditions during the Frederick Street sampling campaign allowed some assessment of the effects of wind speed and turbulence on the measured concentration of pollutants. Importantly, the wind did blow from the East, as well as from the West, for sufficient periods of time, to determine the relative importance of source effects versus the canyon effect in determining the concentrations and distribution of measured pollutants.

## 4.2 Outdoor Air Quality

### 4.2.1 Carbon monoxide

The higher outdoor concentrations of carbon monoxide recorded in South Bridge and Frederick Street than recorded in Princes Street Gardens during the autumn of 1994 are consistent with the proximity of the monitoring sites to traffic compared with the monitoring station in Princess Street Gardens which is 35m from the road. Although none of the measurements suggest that EPAQS or WHO guidelines for outdoor carbon monoxide concentrations were exceeded during the measurement periods, the maximum mean concentrations of carbon monoxide measured over 8 hours in Princes Street Gardens in 1994 was four times greater than the mean for October-November 1994. This suggests that the 10ppm limit for carbon monoxide might conceivably be exceeded in both Frederick Street and South Bridge on rare occasions.

In both South Bridge and Frederick Street, the decrease in outdoor concentrations of carbon monoxide with increasing height above the street is consistent with a canyon effect. Although the presence of queuing traffic in both locations would favour the build-up of carbon monoxide on the West and generally more sheltered side of both streets, the highest outdoor concentrations measured at any instance arose on the sheltered side of the street regardless of whether it was the East or the West side. This suggests that the canyon ...... of the streets does have a significant effect on air quality at different points within each street.

The low concentrations of carbon monoxide measured during periods of high windspeed reflect the importance of wind in dispersing pollutants. Increased airflow over the street increases the turbulence of airflow within the street canyon and the overall exchange of air between the canyon and the overlying atmosphere. The increased turbulence associated with higher windspeeds is reflected in the reduced differential in carbon monoxide concentrations between the two sides of Frederick Street or at different heights above Frederick Street than at lower windspeeds. The absence of a similar relationship between the magnitude of the canyon effect and windspeed in South Bridge might reflect the greater prevalence of turbulent weather and high windspeeds throughout the first monitoring campaign than during the second monitoring campaign. The greater build-up of pollution within both Frederick Street and South Bridge under conditions of low windspeed rather than no wind, may be due to the effects of convection leading to enhanced dispersion on completely still days. In the absence of a breeze, the air within the canyons would have been more effectively heated by sunshine than on the more breezy days, which were also characterised by less continuous sunshine. The absence of any relationship between carbon monoxide concentrations and rainfall reflects the relative insolubility of carbon monoxide gas.

The variation in outdoor carbon monoxide concentrations through time in both South Bridge and in Frederick Street is consistent with the anticipated variations in traffic flow during each 24 hour period and over 7 days of the week. The low night time concentrations of carbon monoxide reflect the low volume of night time traffic. The morning, late afternoon and mid-evening peaks of carbon monoxide concentration all reflect periods of maximum traffic flow. The later morning and earlier afternoon peaks in concentration measured at weekends reflects the leisure rather than business use of the city centre at weekends: people tend to start shopping later and finish shopping earlier than a full working day. The bigger mid evening peak in concentrations at weekends, similarly reflects the difference in social behaviour between the working week and weekends with more people visiting the city centre to eat or for entertainment at the weekend. The lower concentration of carbon monoxide on a Sunday in South Bridge than on other days is consistent with lower traffic flow than on a working day. The less marked difference between Sundays and other days in Frederick Street may be due to the Sunday opening of shops in Princes Street. It probably also may reflect differences in the type of traffic using both streets. Both the number of buses and the number of people travelling into central Edinburgh are much reduced on Sundays relative to other days, giving rise to a marked reduction in traffic flow along South Bridge. A substantial proportion of the traffic in Frederick Street throughout the week reflects leisure rather than business activity and there is therefore a much less marked difference between weekday and weekend traffic flow.

The greater variation in carbon monoxide concentrations through time at any location in either street than the difference in concentrations between locations within each street at any instance suggests that source effects, ie variations in traffic flow, are the dominant effect on local air quality.

The diurnal variation in carbon monoxide concentrations indicates that traffic within South Bridge and Frederick Street was the main source of carbon monoxide within these streets. The preliminary investigations of carbon monoxide concentrations in central Edinburgh, however, indicated that some localised peaks in carbon monoxide concentration were unrelated to traffic, suggesting that pollutants emitted from some buildings may have a significant effect on local air quality.

### 4.2.2 Particulate (PM10) concentrations

The higher particulate concentrations measured in South Bridge and Frederick Street than generally recorded in Princes Street Gardens are consistent with the proximity of the monitoring sites to traffic compared with the monitoring station in Princess Street Gardens which is 35m from the road. The higher PM10 concentrations measured in South Bridge than in Frederick Street reflect the greater flow of buses and commercial vehicles along South Bridge. The relatively low concentrations of particulates measured in South Bridge over weekends as opposed to during the working week are consistent with a much lower traffic flow at weekends, particularly on Sundays. The absence of a similar effect in Frederick Street may, as with the carbon monoxide data, reflect a smaller degree of differentiation in traffic behaviour between weekdays and the weekend.

The number of particulate measurements made was small and the masses of dust collected on filter close to the detection limit of the method. These factors limit any assessment of the importance of the canyon effect in the dispersion of particulate pollution. The higher particulate concentrations measured outside the University Cellar relative to those measured outside Thins are consistent with a canyon effect (Fig. 1), but they could equally be explained by queuing traffic (Fig. 4). The variation in particulate concentrations across Frederick Street is less consistent with a canyon effect, again suggesting that queuing traffic may a greater effect on local particulate concentrations than the canyon effect. Additionally, although the categorization of days suggests that the wind was dominantly from the South-West on virtually all days, the relative influence of winds from the East, on days when Easterly winds prevailed for several hours, has not been assessed. The absence of any marked reduction in particulate concentrations with height above South Bridge contrasts with the Frederick Street data. This might reflect the more turbulent weather that prevailed during the South Bridge monitoring period which would have led to more rapid dispersion within the street.

The proportion of measurements of PM10 concentrations that are greater that $50\mu g^{-3}$ might be of concern, given the new guidelines issued by EPAQS, although previous guides and limits (eg EC, WHO) were much less stringent. The EPAQS limit might already allow for the predictably higher concentrations of particulates that will arise immediately adjacent to traffic than at the EUN measurement sites that are selected to representative of ambient city air, and relatively few people spend a significant proportion of their day outdoors in street canyons. However, the number of pedestrians in street canyons is greatest at time of maximum traffic flow and therefore during periods when particulate concentrations are likely to be particularly high.

#### 4.2.3 Volatile organic compounds

The variation of outdoor concentrations of benzene, toluene and xylene with location in Frederick Street was consistent with a canyon model for at least some of the measurement period (ie the highest concentrations arose at first floor level on the sheltered side of the road), if it is assumed that the major source of all three pollutants was traffic pollution. The scatter plots of benzene versus toluene and xylene concentrations (Fig. 38) do suggest (a) common source(s) for most of the outdoor benzene, toluene and xylene pollution. The scatter plots of benzene or toluene versus carbon monoxide however suggest that although these pollutants have a common source on the East side of Frederick Street, consistent with emissions from petrol driven traffic, they do not share a single common source on the West side (Fig. 43).

The significant number of measurement periods during which mean concentrations were higher at third floor than at first floor level suggest that, over a 24 hour period, the general background levels of pollution have an equally important effect on air quality in Frederick Street as traffic pollution generated itself within the street. In addition, as with the particulate data, the categorization of days by weather may not have been ideal. Possibly the data would have shown clearer evidence of a canyon effect, if sampling had been restricted to periods of high traffic flow. Given that there is no marked difference in benzene:toluene or benzene:xylene ratios on different days (Fig. 38), the sources of these pollutants appear to have been largely similar whether or not the major source on any one day was at street or roof top level. In addition, the benzene data from the Medical School show a three-fold variation in benzene concentrations during the day with concentrations being lowest at night and highest during the morning rush hour (0800-0900). These two observations suggest that the major source of these pollutants in central Edinburgh is traffic pollution. The higher concentrations of benzene measured in Frederick Street than on the roof of the Medical School might reflect a greater proximity to traffic, but may also reflect differences in measurement technique.

#### 4.2.4 Nitrogen dioxide

The nitrogen dioxide ($NO_2$) data are not consistent with the canyon model illustrated in Figure 1, suggesting that traffic pollution generated within Frederick Street itself was not the only major source of $NO_2$ over the measurement period. As with the data for the volatile organic compounds, the absence of a clear canyon effect in the daily mean measurements of $NO_2$ may partly be because although significant amounts of traffic pollution are generated within Frederick Street during the day, at night, the major source of $NO_2$ is more likely to be ambient pollution within the city centre area. In addition, vehicle emissions contain a mixture of nitrogen oxides and the gradual conversion of nitric oxide to nitrogen dioxide within ambient city air may obscure any canyon effect within the $NO_2$ data. A canyon effect might have been detected, if total concentrations of NOx rather than of $NO_2$ alone had been measured. The absence of a positive co-variation between concentrations of PM10 and $NO_2$ also tends to suggest that traffic pollution within the street is not the major source of $NO_2$ as both pollutants are principally emitted by diesel engines. Comparison of the data for Frederick Street with published data for Princes Street Gardens suggest that concentrations in Frederick Street are fairly similar to the background concentrations of $NO_2$ prevalent in central Edinburgh. The diurnal variation in $NO_2$ concentrations measured in Princes Street Gardens shows that concentrations of $NO_2$ arise during the morning and evening rush hour periods consistent with a traffic source. Measurements of nitrogen dioxide concentrations adjacent to a number of major arterial roads in Edinburgh made by the District Council, also indicate that road traffic is a major source of $NO_2$ in city air. Additional sources of nitrogen dioxide in the city centre would include gas-fired heating systems. The concentration of buildings is much higher in the City centre than in the areas included in the EDC surveys, and therefore the proportion of building-derived $NO_2$ in air may be much greater. A further source of $NO_2$ in Princes Street Gardens may be diesel powered locomotives using the railway line that passes through the Gardens.

The relationship between $NO_2$ concentrations and rainfall suggests that some $NO_2$ is washed out from city air by rain and the relationship between $NO_2$ concentrations and windspeed reflects the generally greater dispersion of pollution from the city on windy days than on calmer days.

The mean diurnal variation in nitrogen dioxide concentrations in Princes Street Gardens shows a two-fold difference between minimum concentrations (night time) and maximum concentrations in the summer and a three-fold difference in the winter (DoE data). This suggests that hourly mean concentrations of nitrogen dioxide in Frederick Street might occasionally exceed 100ppb corresponding to the DoE definition of poor air quality.

### 4.2.5 Conclusions

Both the results of the preliminary investigations and systematic measurement campaigns suggest that canyon-like geometry does have a measurable effect on outdoor air quality in Edinburgh streets. The effect is however small and can only be clearly identified from the hourly carbon monoxide data. At any instant in time, the spatial variation in carbon monoxide concentrations that would be expected to arise from the canyon effect for a uniform source within the street (Fig 1), can be completely swamped by the spatial variation in carbon monoxide generation within the street that arises from the presence of queuing traffic within the canyon. The canyon effect is most marked at times of maximum traffic flow, when the concentrations arising from local sources are highest, combined with wind flow perpendicular to the street and conditions of low windspeed.

A simple canyon effect reflecting retardation of dispersion from a uniform source of pollution within the street cannot be clearly detected in pollution measurements made over a 24 hour period. It is possible that although significant amounts of traffic pollution are generated within the street canyons during day time periods, this is counterbalanced by the generation of relatively little traffic pollution at night (0000-0700). During these night time periods, air quality within street canyons is presumably little different from that elsewhere in the city centre. Although the major source of air pollution in the city is traffic-related, the major source of air pollution in street canyons may not necessarily be traffic flow within the individual canyons, but more general traffic flow within the city. In addition, traffic is not the only source of city air pollution and the relative importance of traffic versus other sources of air pollution presumably varied during each 24 hour measurement period. It is possible that, if sampling had been constrained to rush hour periods of maximum traffic flow within the canyons, the particulate, $NO_2$ and benzene (+toluene+xylene) data would have showed a clearer canyon effect on dispersion.

## 4.3 Indoor Air Quality

### 4.3.1 Carbon monoxide

The indoor measurements of carbon monoxide in both South Bridge and Frederick Street suggest high outdoor concentrations of pollutants are likely to be reflected by slightly higher than normal concentrations of pollutants inside. The differences between indoor and outdoor concentrations of carbon monoxide at the different measurement locations largely reflect differences in ventilation in the various rooms used for measurement. The greatest differences between indoor and outdoor concentrations arose in the Woolwich staff room which was the only measurement site where the window was properly closed. The relationship between outdoor and indoor peaks of concentration in the staffroom suggest that even although the window was closed, indoor concentrations of carbon monoxide evolved towards outdoor concentrations over a period of only a few hours. This adjustment might be less rapid in a property with modern well sealed windows. The data for Sun Alliance suggest that for used and unused rooms, there is little difference between inside and outside air quality if the room is ventilated by open windows. The slightly greater difference between indoor and outdoor air quality in the first floor Sun Alliance office at low concentrations of carbon monoxide than at higher concentrations might reflect the fact that the lowest outdoor concentrations arose at times when the greatest number of windows would have been closed ie overnight and during particularly breezy weather.

### 4.3.2 Particulate (PM10) concentrations

The absence of a consistent relationship between indoor and outdoor particulate concentrations may be partly due to the relatively few measurements made and the small masses of dust collected on filter relative to the detection limit of gravimetric analysis.

The tendency for indoor concentrations to be lower than outdoor concentrations, particularly during periods of relatively high outdoor concentrations, may indicate that the transfer of particulate pollution into buildings is less effective that the transfer of gaseous components.

### 4.3.3 Benzene, toluene, xylene

At most of the indoor localities, the dominant source of benzene, toluene and xylene appears to be from external sources. The dominant source of these chemicals within the Woolwich staffroom was however characterised by a much higher toluene to benzene or xylene ratio than the outdoor source. Possible indoor sources of toluene would include cleaning fluids or other solvents. The toluene data indicate that where indoor sources of air pollution are present, these can entirely swamp the effects of external air quality.

### 4.3.4 Nitrogen dioxide

The poor correlation between indoor and outdoor concentrations might suggest that only some of the nitrogen dioxide present indoors has come directly from outdoor sources. In addition the differences may reflect differences in the rate of oxidation of nitric oxide to nitrogen dioxide between the indoor and outdoor environment and reflect the greater potential for $NO_2$ to be washed out of outside air. Alternatively differences in the diurnal variation of $NO_2$ concentrations indoors and outdoors, particularly in the less well ventilated rooms, might give rise to an apparent overall difference in daily mean concentrations indoors and outdoors. This seems unlikely given the good correspondence between indoor and outdoor concentrations of the other pollutants. It is unclear what indoor sources of $NO_2$ might have been present, as none of the rooms contained gas burners or were used by smokers.

### 4.3.5 Conclusions

In the absence of significant indoor sources of pollution, indoor air quality appears to be closely related to outdoor air quality. In most domestic premises however, the sources of indoor pollution are probably much greater than in the properties in South Bridge and Frederick Street and more work is needed to determine the importance of outdoor air quality in determining indoor air quality particularly in domestic premises.

There appears to have been relatively little dilution of gaseous pollutants in the indoor environments relative to the outdoor environments whereas indoor concentrations of particulates appear to have been considerably diluted relative to outdoor concentrations. This suggests that the transport of particulate pollution from indoors to outdoors is much less effective than that of gaseous pollutants. The transport of particulate pollution is however likely to be determined by particle size and the ultrafine component of PM10 may be almost as efficiently transported as gaseous components. The coarsest components of PM10, which would have the greatest effect on measured mass concentrations, are likely to be the least efficiently transported. The peaks in concentration of pollution measured outdoors appear to be much less marked indoors. This suggests, that in the absence of substantial indoor sources of pollution, any acute respiratory effects (eg asthma) that might result from momentary exposure to relatively high levels of pollution would be less likely to arise indoors than outdoors. In contrast, the cumulative exposure to pollution would appear to be very similar in the outdoor and indoor environments monitored, suggesting that for carcinogens such as benzene, the relative hazard is the same for those exposed to indoor or outdoor air (in the absence of substantial indoor sources of pollution such as solvents).

In rooms ventilated by open windows, there is little difference between indoor and outdoor air quality at any instant in time. Other methods of ventilation might give rise to a greater difference between indoor and outdoor air quality. Where the windows are closed, there may a marked difference in the indoor and outdoor concentrations of any pollutant at any instant in time. However (for a room with traditional, single glazed, wooden windows), it appears to take only a few hours for changes in outdoor air quality to be reflected by similar, though less marked changes in indoor air quality. Further work is required to determine whether indoor and outdoor air quality would be so closely related in rooms with closed, modern, well sealed, double glazed windows.

### 4.4 Possible Health Effects Associated with Pollution in Street Canyons

The measured concentrations of carbon monoxide, toluene and xylene measured both indoors and outdoors are much lower than those associated with observable health effects (WHO, 1979; Wallace, 1991).

Benzene is a carcinogen and therefore there are no safe limits of exposure. The risk of developing leukaemia as a result of benzene exposure in street canyons is however small ($3.6 \times 10^{-5}$ for the highest measured mean concentration of benzene, WHO 1993). The higher measured concentrations of benzene within the street canyons than in Princess Street Gardens suggest that the risk of developing leukaemia as a result of exposure to benzene might be slightly greater for those working and living in narrow city streets than for those who live and work in more open areas of the city, away from busy traffic routes.

The measured concentrations of nitrogen dioxide suggest that short terms in concentration may occasionally be sufficient to lead to localised short episodes of poor (but not very poor) air quality in street canyons. It is possible that these episodes of poor air quality could trigger symptoms in the most susceptible members of the population such as some asthmatics and those with other pre-existing lung disease (DH, 1993). Comparison of the measured concentrations of nitrogen dioxide in Frederick Street with the DoE data for Princes Street Gardens suggests that there is little or no greater likelihood of the development of poor air quality with respect to nitrogen dioxide in street canyons than elsewhere in central Edinburgh. It does not appear, therefore, that any risks to health associated with nitrogen dioxide will be higher in street canyons than elsewhere in the city. The data also suggest that indoor and outdoor concentrations of nitrogen dioxide may be fairly similar, in the absence of significant indoor sources of nitrogen dioxide. This suggests that there may be little advantage for those suffering from asthma or other chronic lung disease in remaining indoors during high pollution episodes.

The measured concentrations of PM10 suggest that the possible risks to health due to exposure to fine particulate matter are much greater in street canyons than elsewhere in the city. Comparison of the indoor and outdoor data suggests that exposure to fine particulates and thus the risk of associated health effects is much lower indoors than outdoors. The mean outdoor concentration of PM10 measured in South Bridge was more than double the mean for September-October 1993 in Princes Street Gardens. The difference in particulate concentrations between the two locations would equate to a 3% increase in daily mortality, a 1.5% increase in admissions to hospital for respiratory disorders and a 15% increase in asthmatics with exacerbated symptoms (Table 1). It is however difficult to really determine how much greater the risks of developing respiratory symptoms in street canyons is, compared with elsewhere in the city, because of the limited information available about personal exposure to pollution. In particular, in the absence of significant sources of indoor particulate pollution, indoor concentrations of PM10 appear to be less different from the concentrations measured in Princes Street Gardens, than outdoor concentrations. In addition, in premises where there are significant indoor sources of particulate pollution such as tobacco smoke, indoor concentrations of PM10 may greatly exceed those prevalent outdoors and only be slightly affected by changes in outdoor concentrations.

## 4.5 Suggestions for Further Work

The literature review (Appendix 1) identified a number of issues that the measurement phase of the project might usefully address. The resources available for the measurement phase were however limited and a more tightly targeted approach had to be adopted. Many of the issues identified in the literature review are therefore still worthy of further investigation. In addition, the data from the measurement campaigns themselves suggest that there a number of other issues worthy of further investigation.

The data collected to date by the IOM, does suggest that the canyon effect is detectible in Edinburgh streets. However, as sampling strategy was limited by the amount of resource available, it was only possible to make a limited assessment of the relative importance of traffic factors and building geometry in determining air quality within South Bridge or Frederick Street. In retrospect it would have been useful to have been able to monitor the lateral variation in pollutant concentrations within one of the canyons and to link that with traffic behaviour and building geometry. One of the limitations in making measurements at street level, was the security of our instruments and more importantly of any premises that were used for measurements. There are two approaches that could be useful: to set the carbon monoxide monitors up to run only over a selected number of rush hour periods and to man the instruments throughout the sampling periods or to use diffusive samplers that could be attached to buildings for several weeks and left unattended. The advantages of the first approach would be that the canyon effect appears to be most readily detectible during rush hour periods and the carbon monoxide monitoring could be combined with a semi-quantitative traffic census and record of the build-up of traffic queues. The scope of the measurements could be expanded to include measurements of outdoor carbon monoxide concentrations in a wider range of streets which would improve information about relative role of traffic flow versus canyon effect. In addition it would be useful to compare concentrations at the kerbside versus those at shop fronts and concentrations in an adult's versus toddler's breathing zone. The advantages of the second approach would be that a) much better spatial resolution could be achieved, b) it should be relatively inexpensive, and c) arguably the long term mean concentrations of pollutants are a better measure of the real importance of the canyon effect than short term measurements made at times when the canyon effect is probably of greatest significance.

The particulate data suggest that concentrations of PM10 in Edinburgh streets are frequently greater than the $50\mu gm^{-3}$. This would seem to be worthy of further investigation. Firstly it would be desirable to improve the precision of our measurements, both through use of more appropriate sampling media and through multiple rather than simply duplicate weighings of each sample (which would require rather more resource than the gravimetric analyses undertaken to date). It would also be desirable to widen the scope of the measurements to include more residential streets with lower traffic flows and some major traffic routes that do not have noticeably canyon-like geometries. One of the limitations of the IOM personal sampler as a measurement device is that measured concentrations of PM10 were averaged over 24 hours or longer. It might be more relevant to invest in one of the various types of continuous monitoring systems for particulates that are now available and to examine shorter term variations in concentration that could be related to traffic movement or weather factors.

Both resource and logistical considerations limited the information that has been collected about air quality in tenement flats. This could be addressed in a future measurement campaign by making a detailed comparison of indoor and outdoor concentrations of pollutants in a range of individual properties that include both traditional tenement flats and a variety of more modern residences. It would be logistically much more realistic to identify suitable individual properties than attempting to recruit residents in the clusters of properties that were needed to initially test the relevance of the canyon model to Edinburgh.

# 5. CONCLUSIONS

The results of pollution monitoring undertaken by the IOM for The Scottish Office indicate that:

5.1 The canyon geometry of some city streets does have a detectible effect on the dispersion of traffic pollution, particularly if hourly mean (rather than daily mean) concentrations are considered.

5.2 The daily mean outdoor concentrations of some pollutants (nitrogen dioxide, particulates) do not show consistent evidence of a canyon effect suggesting that local traffic sources of these pollutants in some streets are small relative to general urban background concentrations (although the background concentrations may themselves be largely the result of traffic pollution).

5.3 The EPAQS (1995) guidelines for particulate concentrations measured as PM10 ($50\mu gm^{-3}$) appear to be frequently exceeded in city streets. The guides and limits for other pollutants appear to be rarely, if ever, exceeded. It is possible that hourly mean concentrations of nitrogen oxide are high enough for air quality within street canyons to be considered poor, on several occasions during any single month.

5.4 Daily mean concentrations of most of the pollutants measured appear to be greater in street canyons than at the EUN monitoring sites. This suggests that guides and limits for daily mean (and hourly mean) concentrations of some pollutants (particulates, benzene) may be exceeded more often in street canyons that at the EUN monitoring sites. Daily mean concentrations of other pollutants (nitrogen dioxide) do not appear to be greater in street canyons than at the EUN monitoring sites.

5.5 In the absence of significant indoor sources of pollution, indoor concentrations of gaseous pollutants appear to be similar to outdoor concentrations, whereas indoor concentrations of PM10 are generally much lower than outdoor concentrations. Peak outdoor concentrations of pollutants, particularly when measured over 1 hour rather than 24 hour periods, give rise to higher than normal indoor concentrations, but maximum indoor concentrations of pollutants are less than maximum outdoor concentrations. In rooms that are well ventilated by open windows there are no significant differences in indoor and outdoor concentrations at any instant in time. In less well ventilated rooms the diurnal variation in pollution concentrations is lagged with respect to the outdoor diurnal variation.

5.6 The build up of pollutants due to the presence of queuing traffic can have a greater effect on local air quality than the canyon effect with high concentrations of pollution arising, in open environments that are relatively distant from tall buildings.

5.7 Traffic is only one of several urban sources of air pollution and both the $NO_2$ data and the preliminary carbon monoxide measurements indicate that building sources of pollution may be locally significant.

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# 7. REFERENCES


Aitkin RJ, Donaldson R. (1995). Development and testing of size-selective personal aerosol sampling instruments based on porous foam selectors. Paper presented The American Industrial Hygiene Conference and Exposition. Kansas, Missouri

Comité Européen de Normalisation (CEN). (1992). Size fraction definitions for the measurement of airborne particles in the workplace pr EN 481.

Coultas DB, Lambert WE. (1991). Carbon Monoxide. In: Indoor Air Pollution (ed. JM Samet, JD Spengler) John Hopkins University Press. Baltimore and London. pp187-208.

Department of the Environment. (1995). Air Pollution in the UK: 1993/4. AEA Technology. 409pp

Department of Health. (1993). Oxides of nitrogen. Third Report of the Advisory Group on the Medical Aspects of Air Pollution Episodes, HMSO, 137pp.

Dockery DW, Spengler JD. (1981). Indoor-outdoor relationships of respirable sulfates and particles. Atmos. Environ, 15: 335-345

Expert Panel on Air Quality Standards. (1994). Carbon Monoxide. Department of the Environment, HMSO, London, 24pp

Expert Panel on Air Quality Standards. (1995). Benzene. Department of the Environment, HMSO, London, 20pp

Expert Panel on Air Quality Standards. (1995). Particles. Department of the Environment, HMSO, London, 30pp

Health and Safety Executive. (1987). Methods for the determination of hazardous substances, Benzene in air: laboratory method using charcoal absorbent tubes, solvent desorption and gas chromatography. MDHS 17. HSE London 1987.

Hoydysh WG, Dabberdt WF. (1988). Kinematics and dispersion characteristics of flows in assymetric street canyons. Atmos Environ: 22: 2677-2689.

Luria M, Weisinger R, Peleg M. (1990). CO and NOx levels at the centre of city roads in Jerusalem. Atmos Environ: 24B: 93-99

NIOSH. (1978). Nitrogen dioxide. Method No. S320. United States Department of Health, Education and Welfare. National Institute of Occupational Safety and Health Manual of Analytical Methods. Second Edition: Volume 4.

Quality of Urban Air Review Group. (1993). Urban air quality in the United Kingdom. Department of the Environment, Bradford. 202pp.

Samet JM, Cain WS, Leaderer BP. (1991). Environmental Tobacco Smoke. In: Indoor Air Pollution (ed. JM Samet, JD Spengler) John Hopkins University Press. Baltimore and London. pp131-169

Spengler JD, Samet JM. (1991). A perspective on Indoor and Outdoor Air Pollution. In: Indoor Air Pollution (ed. JM Samet, JD Spengler) John Hopkins University Press. Baltimore and London. pp1-32.

Spengler JD, Sexton. (1983). Indoor air pollution: a public health perspective. Science 221:9-17.

Spengler, *et al.* (1983). Nitrogen dioxide inside and outside 137 homes and implications for ambient air quality standards and health effects research. Environ. Sci. Technol. 17: 164-168

Wallace LA. (1991). Volatile Organic Compounds. In: Indoor Air Pollution (ed. JM Samet, JD Spengler) John Hopkins University Press. Baltimore and London. p252-272

World Health Organization, Regional Office of Europe. (1995). Update and revision of Air Quality Guidelines for Europe. Meeting of the Working Group "Classical" Air Pollutants, Bilthoven, Netherlands, 11-14 October 1994. WHO: Copenhagen, 1995.

World Health Organization. (1979). Carbon monoxide. Environmental Health Criteria, 13, International Programme on Chemical Safety, Geneva, 125pp.

World Health Organization. (1985). Toluene. Environmental Health Criteria, 52, International Programme on Chemical Safety, Geneva, 146pp.

World Health Organization. (1993). Benzene. Environmental Health Criteria, 150, International Programme on Chemical Safety, Geneva, 157pp.

**Table 1:** **Estimated health effects of a 10$\mu$gm$^{-3}$ increase in daily mean PM10 concentration based on information collated by the World Health Organisation (WHO, 1995)**

| **Human health effect indicator** | **%change/10$\mu$gm$^{-3}$PM10** |
|---|---|
| Daily mortality | 1 |
| Hospital admissions for respiratory conditions | 0.5 |
| Numbers of asthmatic patients using extra bronchodilators | 7 |
| Numbers of asthmatic patients with exacerbated symptoms | 5 |

**Table 2:** **Summary of guide and limit values for measured pollutants including limits for total dust and Black Smoke as alternative measures of particulate concentrations**

| **Pollutant** | **EPAQS** | **EC limits** | **EC guides** | **WHO** | **OEL/ 40** |
|---|---|---|---|---|---|
| carbon monoxide (ppm) | 10 | | | 10 (8 hrs)*<br>25 (1 hr)<br>50 (30 mins)<br>87 (15 mins) | |
| nitrogen dioxide (ppb) | poor: 100-299**<br>very poor: >299** | 26.2 (annual median);<br>104.6 (98th percentile) | 70.6 (98th percentile) | 80(day)<br>16 (annual mean)<br>50(1hr) | |
| PM10 ($\mu gm^{-3}$) | 50 | | | 70 (combined with $SO_2$> 48ppb) | |
| Total dust ($\mu gm^{-3}$) | | 150 (annual mean);<br>300 (98th percentile of daily means) | | 120 (daily mean) | 250 |
| Black smoke ($\mu gm^{-3}$) | | 68 (annual median);<br>213 (98th percentile of daily means) | 34-51 (annual mean);<br>85-128 (daily mean) | 125 (daily mean)<br>50 (annual mean) | |
| Benzene (ppb) | 5 | | | | 125 |
| Toluene (ppb) | | | | | 1250 |
| Xylene (ppb) | | | | | 2500 |

*** the WHO guidelines are given in terms of blood carboxyhaemoglobin levels**
**** DoE air quality guidelines for hourly mean concentrations**

**Table 3:** **Summary of relevant DoE air quality data measured in Edinburgh during 1994. The concentrations of carbon monoxide, PM10 and nitrogen dioxide were measured in Princes Street Gardens and of benzene on top of the Medical School. Given that most of our measurements were made during the month of October 1995, the DoE data for October 1994 are shown for comparison.**

| **Pollutant** | **Annual Mean** | **Maximum daily mean** | **Maximum hourly mean** | **October mean** | **Maximum hourly average in October** |
|---|---|---|---|---|---|
| Carbon monoxide (ppm) | 0.6 | 3.8 | 8.3 | 0.9 | 2.9 |
| PM10 ($\mu gm^{-3}$) | 20 | 62 | 307 | 21 | 307 |
| nitrogen dioxide (ppb) | 27 | 53 | 91 | 28 | 77 |
| benzene (ppb) | 0.7 | 3.7 | 10.7 | 0.9 | 8.7 |

**Table 4:** **Summary of carbon monoxide (CO) data for South Bridge. The sampling periods were essentially over 24 hours, Monday to Friday, and 72 hours over weekends (Friday - Monday). Note that the sampling periods for Thins (East side of South Bridge) exclude the night time periods (2200-0600).**

| | **Mean Conc. CO (ppm)** | **Range of Mean Conc. CO for Each Sampling Period (ppm)** | **Range of Hourly Mean Conc. (ppm)** |
|---|---|---|---|
| Thins 1st Floor - outside | 2.56 | 1.50-6.20 | 1.2-11.4 |
| Thins 2nd Floor - outside | | | |
| *Thins 2nd Floor - inside* | *1.78* | *0.87-2.96* | *0.7-4.4* |
| Thins 3rd Floor - outside | 1.67 | 1.30-2.36 | 0.9-3.3 |
| University cellar - outside | 2.70 | 1.93-3.53 | 1.6-5.4 |
| *University cellar - inside, 1.5m up* | *1.62* | *1.26-2.40* | *1.0-3.6* |
| *University cellar -inside, floor* | *1.49* | *1.18-2.30* | *0.8-3.5* |

**Table 5:** **Concentrations of particulate matter (measured as PM10) measured in South Bridge. The mean concentrations are time weighted and based on the number of samples shown in the final column and include weekday samples (24 hour periods) and weekend samples (72 hour periods). The mean weekend concentrations are each based on only one or two samples.**

| | **Mean Conc. PM10 ($\mu gm^{-3}$)** | | **Range of Daily (or weekend) Mean Conc.** | **% > $50\mu gm^{-3}$** | **No. of Samples** |
|---|---|---|---|---|---|
| | **Mean** | **Weekend** | | | |
| Thins 1st Floor - outside | 26.6 | 4.0 | 4.0-57.8 | 12.5 | 8 |
| Thins 2nd Floor - outside | 22.6 | 13.7 | 6.9-97.6 | 8.3 | 12 |
| *Thins 2nd Floor - inside* | *21.1* | *15.0* | *3.4-51.9* | *9.0* | *11* |
| Thins 3rd Floor - outside | 22.8 | 4.4 | 8.9-48.1 | 0.0 | 10 |
| University cellar - outside | 54.2 | 28.6 | 26.0-135.5 | 53.3 | 15 |
| *University cellar - inside* | *25.0* | *21.2* | *10.1-39.8* | *0.0* | *12* |

**Table 6:** **Mean carbon monoxide (CO) concentrations (mean of daily means) measured in Frederick Street**

| | **Mean Conc. CO (ppm)** | **Range of Daily Mean Conc. CO (ppm)** | **Range of Hourly Mean Conc. (ppm)** |
|---|---|---|---|
| Sun Alliance 1st outside | 2.07 | 1.23-2.94 | 0.8-8.1 |
| *Sun Alliance 1st inside* | *3.18* | *1.60-4.45* | *0.8-7.5* |
| Sun Alliance 3rd outside | 1.50 | 0.62-2.36 | 0.4-6.7 |
| *Sun Alliance 3rd inside* | *1.55* | *0.62-2.23* | *0.4-5.4* |
| Woolwich 1st outside | 3.38 | 2.19-4.14 | 1.7-7.2 |
| *Woolwich 1st inside* | *2.27* | *0.95-2.94* | *0.3-5.0* |
| Woolwich 3rd outside | 1.75 | 1.46-2.09 | 1.0-4.4 |
| *Woolwich 3rd inside* | *2.08* | *1.72-2.44* | *1.0-6.4* |

**Table 7:** **Mean concentrations of particulate matter (measured as PM10) measured in Frederick Street. The mean concentrations are time weighted and based on the number of samples shown in the final column and include weekday samples (24 hour periods) and weekend samples (72 hour periods). The mean weekend concentrations are each based on only one or two samples.**

| | **Mean Conc. PM10 ($\mu g\ m^{-3}$)** | | **Range of Daily Mean Conc.** | **% $> 50 \mu gm^{-3}$** | **Number of Samples** |
|---|---|---|---|---|---|
| | **Mean** | **Weekend** | | | |
| Sun Alliance 1st outside | 48.5 | 49.5 | 4.0-80.6 | 33% | 6 |
| *Sun Alliance 1st inside* | *47.9* | *76.1* | *13.1-76.1* | *33%* | *8* |
| Sun Alliance 3rd outside | 37.6 | 44.1 | 3.4-82.3 | 17% | 7 |
| *Sun Alliance 3rd inside* | *24.6* | *19.3* | *19.3-59.4* | *20%* | *5* |
| Woolwich 1st outside | 41.2 | 40.65 | 7.9-92.7 | 29% | 7 |
| *Woolwich 1st inside* | *28.9* | *35.0* | *7.1-59.0* | *14%* | *7* |
| Woolwich 3rd outside | 27.0 | 3.0 | 3.0-77.8 | 20% | 5 |
| *Woolwich 3rd inside* | *33.2* | *27.3* | *1.7-80.2* | *16%* | *6* |

**Table 8:** **Mean concentrations of benzene, toluene and xylene (ppb) measured in Frederick Street. The mean concentrations are time weighted and based on the number of samples shown in the final column and include weekday samples (24 hour periods) and weekend samples (72 hour periods). The mean weekend concentrations, shown in brackets are each based on only two samples.**

| | **Benzene** | **Toluene** | **Xylene** | **No. of Samples** |
|---|---|---|---|---|
| Sun Alliance 1st outside | 2.2 (2.2) | 5.5 (6.6) | 5.3 (6.8) | 11 |
| *Sun Alliance 1st inside* | *2.2 (2.2)* | *5.7 (7.2)* | *5.2 (6.6)* | *11* |
| Sun Alliance 3rd outside | 2.1( 2.1) | 5.2 (5.4) | 4.5 (5.0) | 10 |
| *Sun Alliance 3rd inside* | *2.0 (2.0)* | *4.4 (4.6)* | *4.2 (4.4)* | *11* |
| Woolwich 1st outside | 2.5 (2.3) | 7.2 (7.9) | 6.2 (5.7) | 12 |
| *Woolwich 1st inside* | *2.1 (2.0)* | *21.4 (18.4)* | *6.3 (6.8)* | *12* |
| Woolwich 3rd outside | 2.8 (3.8) | 10.2 (13.7) | 6.4 (7.4) | 9 |
| *Woolwich 3rd inside* | *1.8 (1.9)* | *8.4 (9.2)* | *5.2 (5.4)* | *9* |

**Table 9:** **Ranges of mean concentrations of benzene, toluene and xylene (ppb) measured in Frederick Street over each measurement period: 24 hours for weekday samples and 72 hours for weekend samples.**

| | **Benzene** | **Toluene** | **Xylene** |
|---|---|---|---|
| Sun Alliance 1st outside | 1.8-3.8 | 2.2-8.1 | 2.0-7.3 |
| *Sun Alliance 1st inside* | *1.4-3.5* | *2.4-8.7* | *1.7-7.9* |
| Sun Alliance 3rd outside | 0.8-3.3 | 1.7-10.6 | 1.5-8.4 |
| *Sun Alliance 3rd inside* | *1.0-3.4* | *1.4-7.1* | *0.0-7.2* |
| Woolwich 1st outside | 0.0-4.6 | 0.0-13.6 | 0.0-15.2 |
| *Woolwich 1st inside* | *1.4-3.2* | *4.7-47.8* | *1.1-10.5* |
| Woolwich 3rd outside | 0.0-5.7 | 3.1-21.0 | 2.9-9.8 |
| *Woolwich 3rd inside* | *0.0-2.7* | *5.2-11.2* | *1.4-7.5* |

**Table 10:** **Concentrations of nitrogen dioxide (ppb) measured at each locality. The mean concentrations are time weighted and based on the number of samples shown in the final column and include weekday samples (24 hour periods) and weekend samples (72 hour periods). The mean weekend concentrations, shown in brackets are each based on only two samples.**

| | Mean Conc. Nitrogen Dioxide | | Range of Daily Mean Conc. | Number of Samples |
|---|---|---|---|---|
| | Mean | Weekend | | |
| Sun Alliance 1st outside | 30.3 | 36.6 | 13.4-41.5 | 12 |
| *Sun Alliance 1st inside* | *32.6* | *31.2* | *17.0-49.2* | *12* |
| Sun Alliance 3rd outside | 31.6 | 38.1 | 2.5-46.3 | 11 |
| *Sun Alliance 3rd inside* | *26.7* | *26.6* | *16.0-41.5* | *11* |
| Woolwich 1st outside | 20.0 | 22.1 | 4.3-40.0 | 11 |
| *Woolwich 1st inside* | *11.5* | *9.3* | *6.8-18.5* | *10* |
| Woolwich 3rd outside | 24.1 | 18.7 | 6.2-34.9 | 9 |
| *Woolwich 3rd inside* | *25.0* | *22.8* | *17.1-34.0* | *9* |

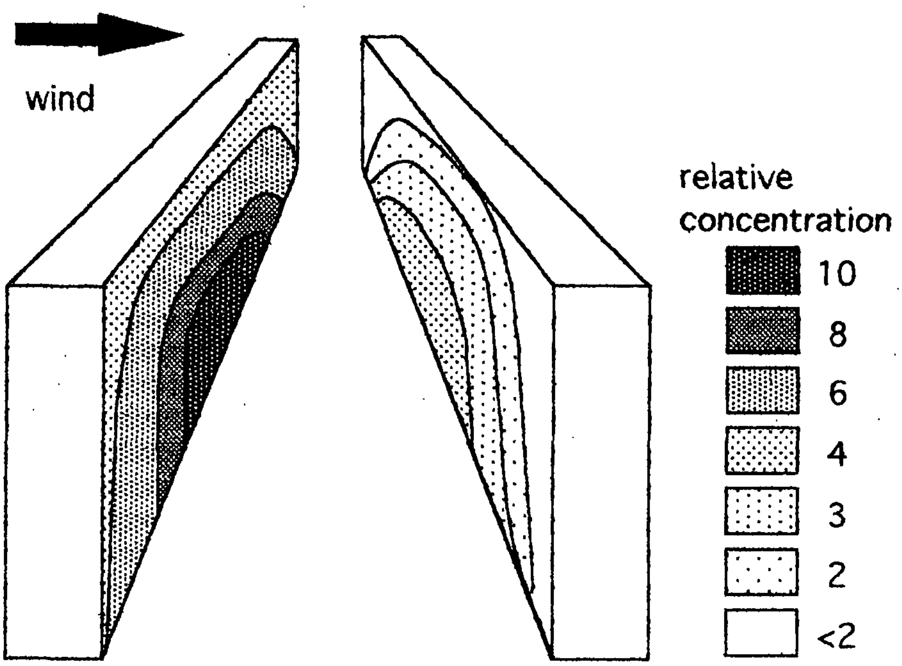



Figure 1: The canyon model: summary of data from model simulations described by Hoydysh and Dabberdt (1988). The two blocks represent the walls of a street canyon as seen in perspective. The relative build-up of pollutants from street (ie traffic) sources is shown in terms of normalised concentrations ($m^{-1}$), ie, the measured concentration of pollution multiplied by wind speed and divided by the rate of pollutant production per unit length canyon. In the case shown, the wind is blowing perpendicular to the street and the maximum build-up of pollution from street sources is mid-block on the sheltered side of the street. In Edinburgh, where the prevailing wind is from the west, this would normally be the west side of north-south trending streets.

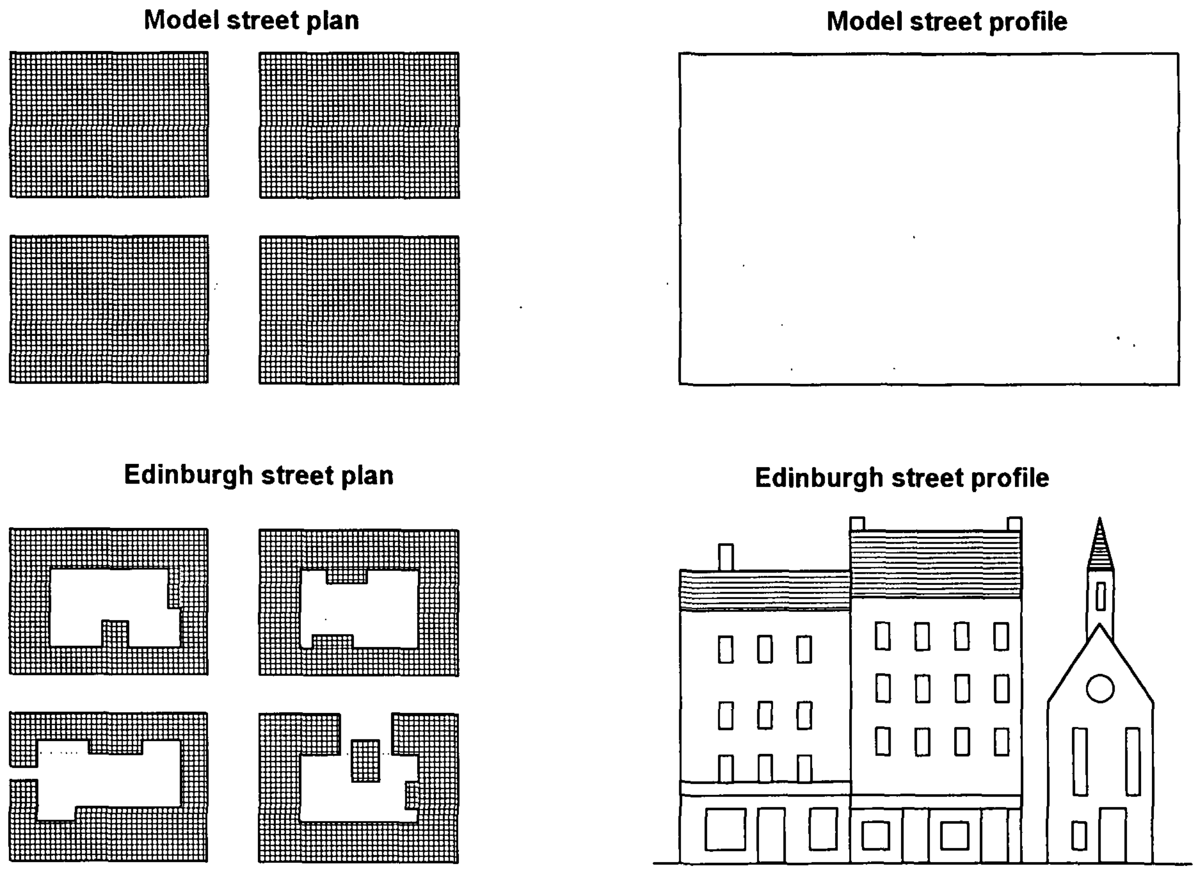



Figure 2: Sketch illustrating the differences between the model streets used in the simulations and real city streets, in both plan view and in terms of vertical street profile.

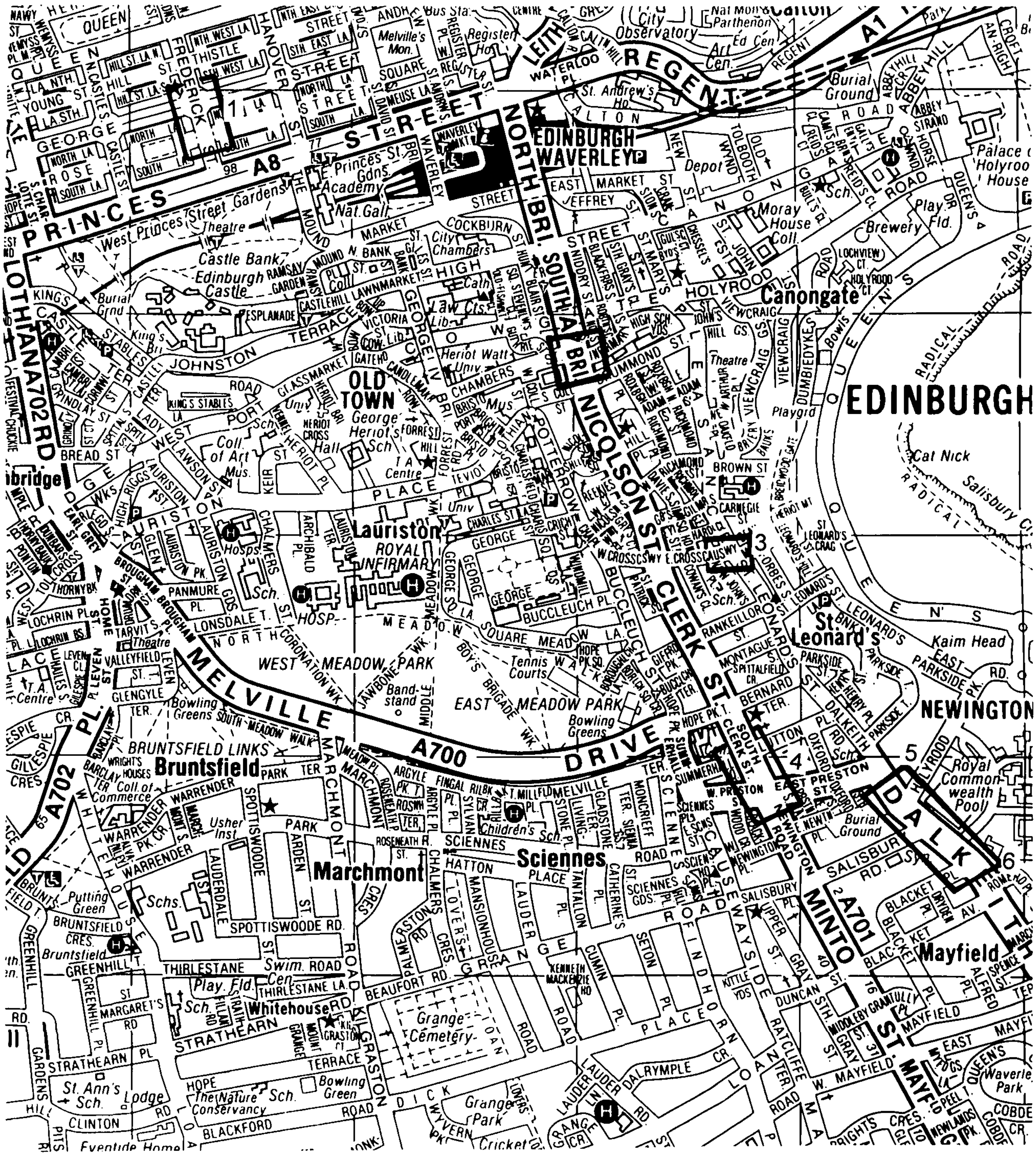



Figure 3: Street map of central Edinburgh showing localities referred to in the text - South Bridge, Frederick Street, South Clerk Street, Dalkeith Road, St. Leonards Street, the High Street.

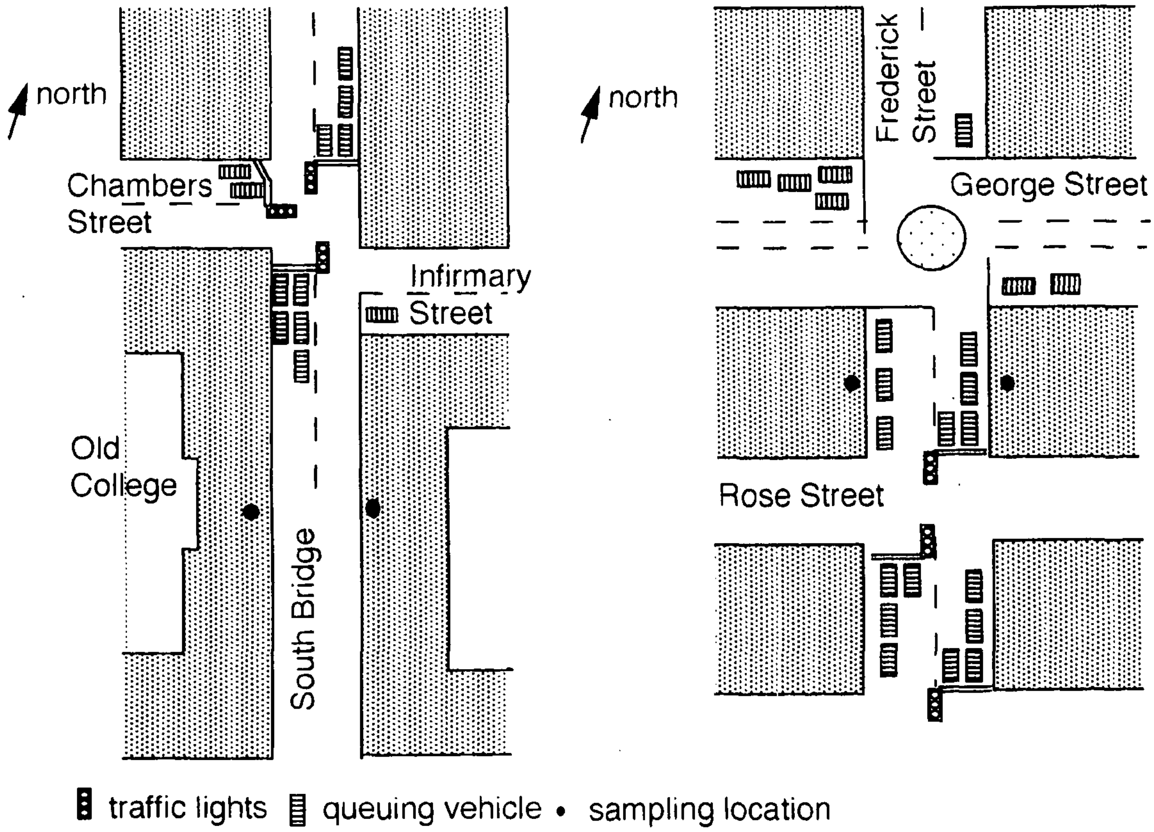



Figure 4: Spatial relationships between traffic control measures such as pedestrian crossings and the monitoring sites in South Bridge and Frederick Street.

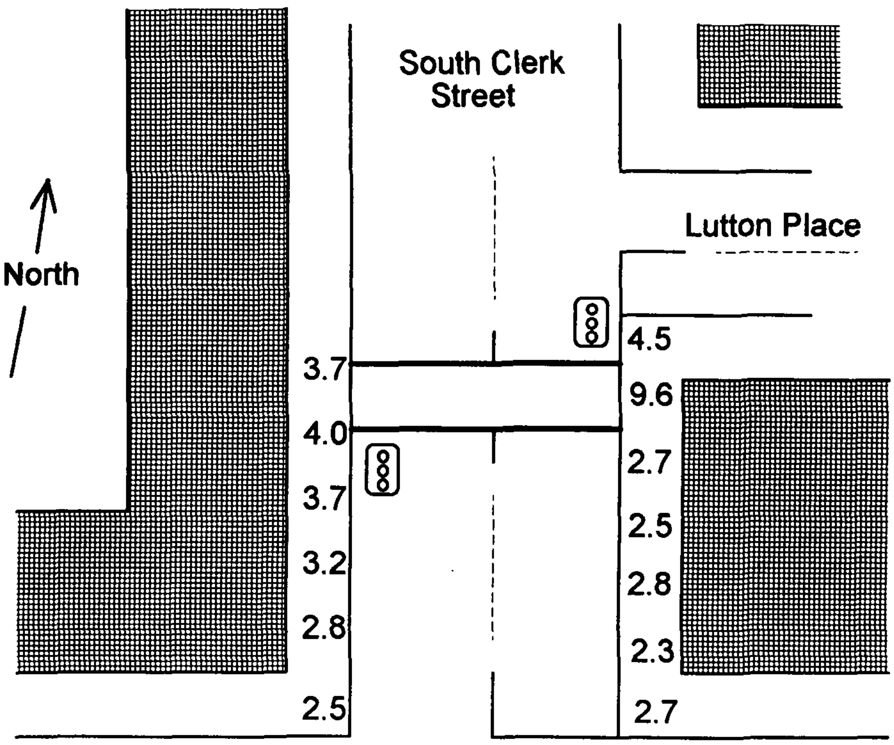



Figure 5: Summary of preliminary carbon monoxide measurements made in South Clerk Street showing the mean outdoor concentrations of carbon monoxide (in ppm) as measured mid evening on six days in late May and early June when the wind was from the West (ie between the Southwest and Northwest).

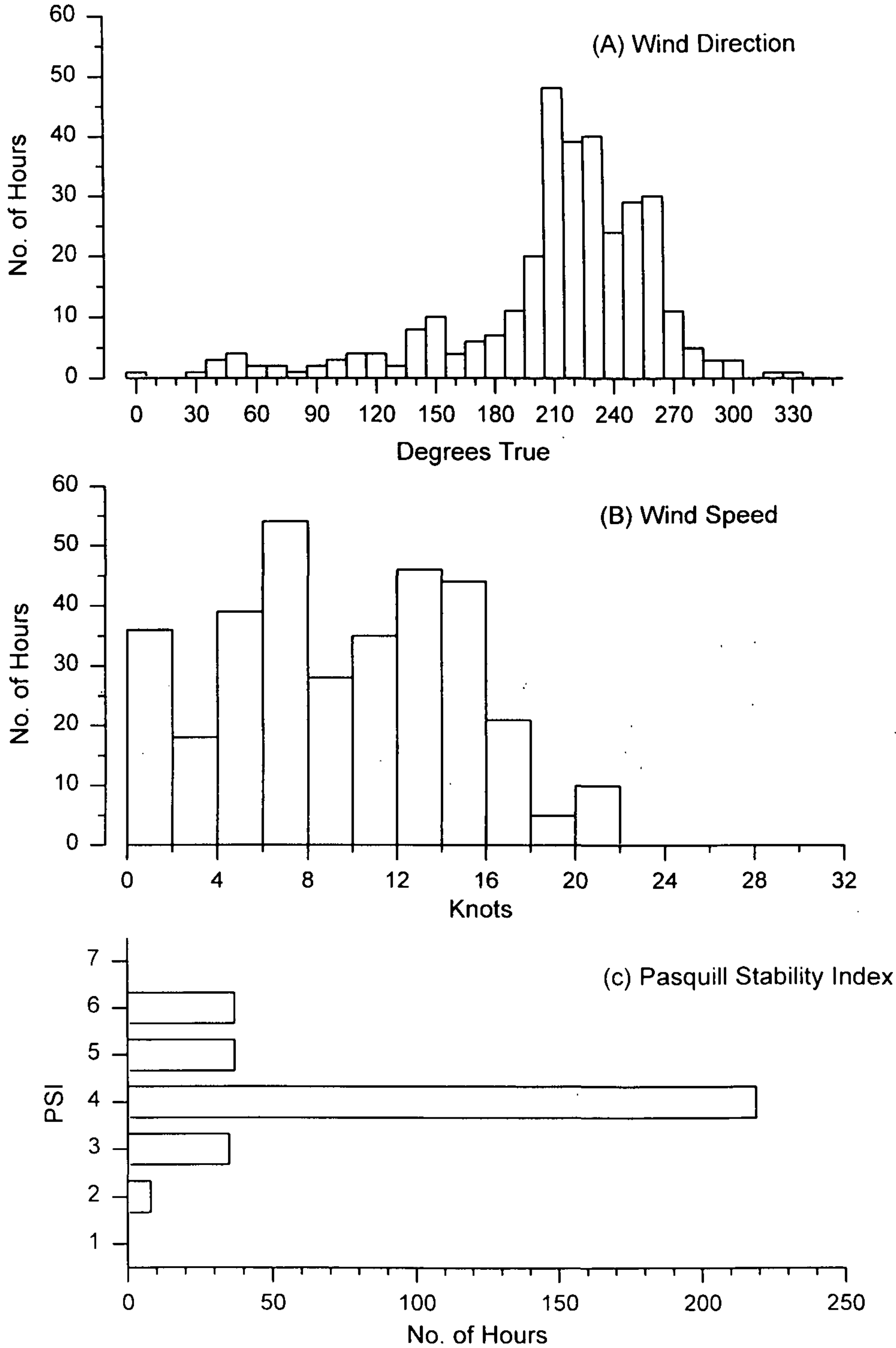



Figure 6: Summary of hourly weather conditions at Edinburgh Airport for the period covering the South Bridge measurement campaign (28/9/95 to 11/10/95); a) wind direction data measured in degrees from true North b) windspeed data; c) hourly Pasquill Stability Index.

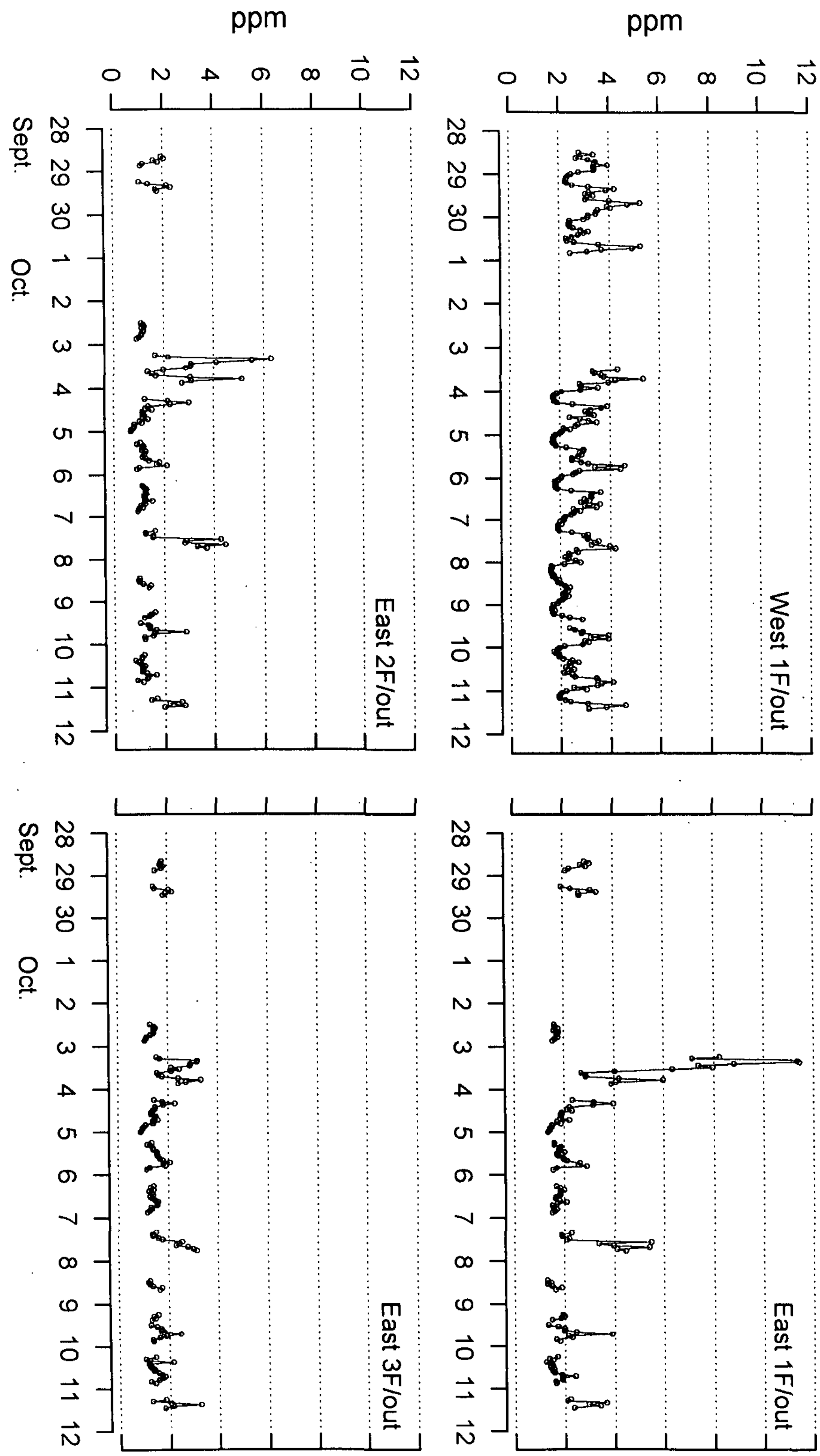



Figure 7: Time series plots of hourly outdoor carbon monoxide measurements made in South Bridge. The measurements on the West side of South Bridge were made outside the cellar (1F/out). Those on the East side were made outside first (1F/out), second (2F/out) and third (3F/out) floor windows. The 1st and 8th of October were Sundays.

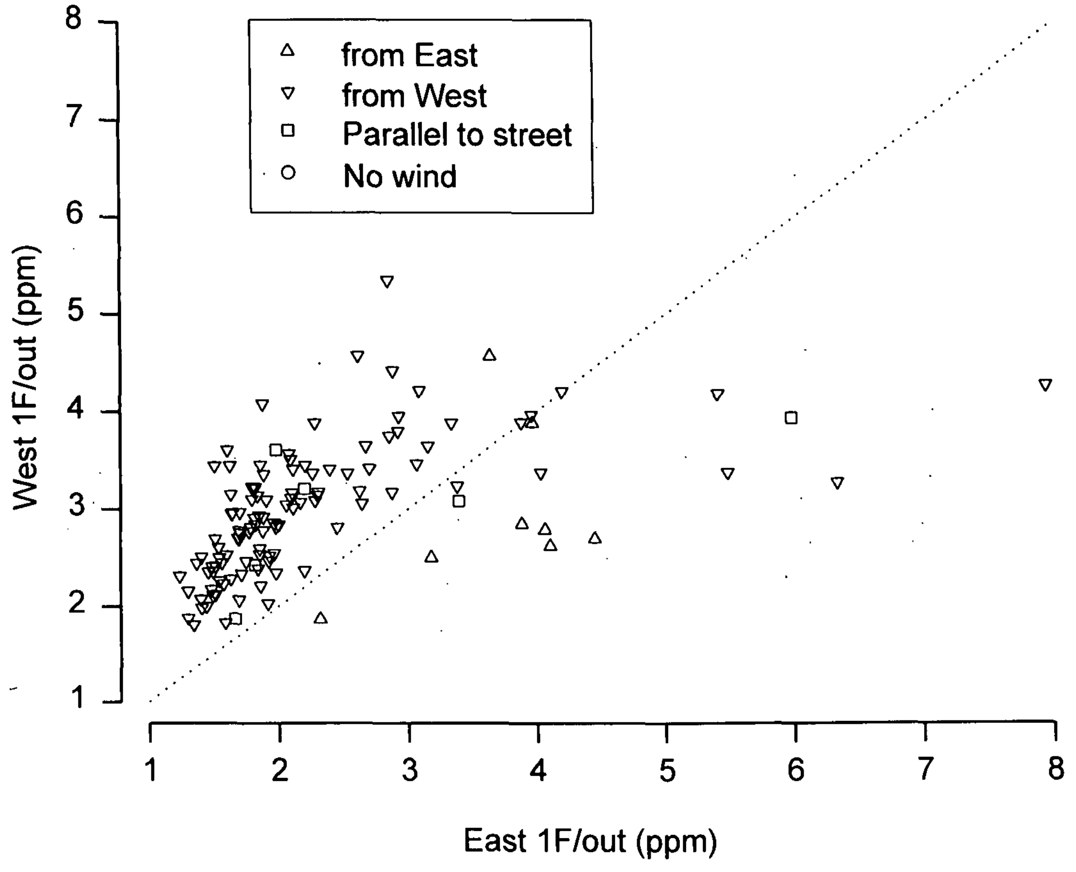



Figure 8: Relationship between concentrations of carbon monoxide measured outside the cellar on the West side of South Bridge (West 1F/out) and outside the first floor (East 1F/out) on the East side, for four categories of wind direction. Dotted line represents the line of equality.

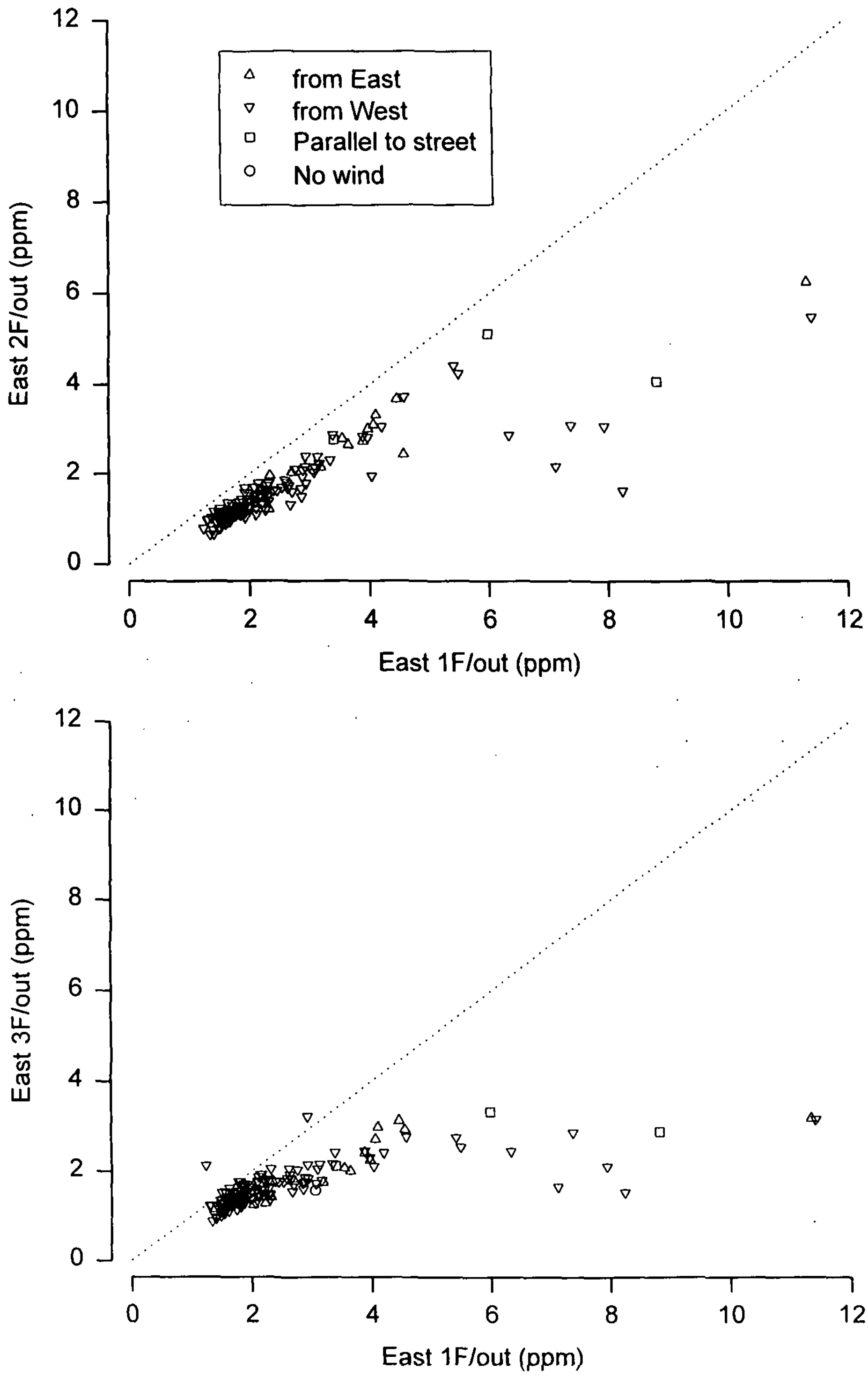



Figure 9: Relationship between outdoor carbon monoxide concentrations measured at different heights above South Bridge (East side). 1F = first floor, 2F = second floor and 3F = third floor. Dotted line represents the line of equality.

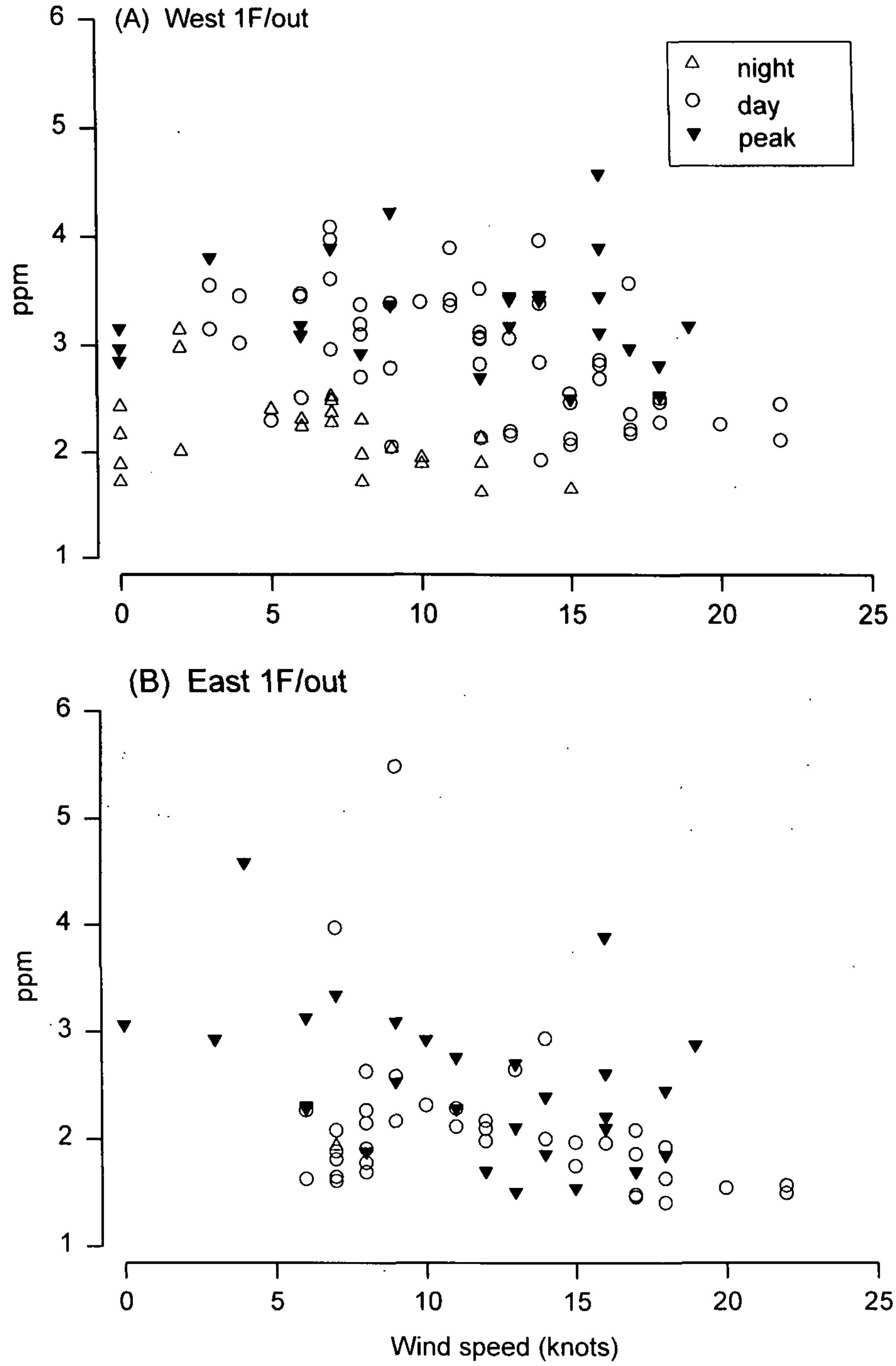



Figure 10: Relationship between the outdoor carbon monoxide concentrations measured in South Bridge and windspeed labelled by time of day. Night is defined as 00.00 to 07.00, peak times are defined as the periods 07.00 to 10.00 and 16.00 to 19.00 on all days excluding Sundays and day covers all remaining time: 10.00-16.00 and 19.00-24.00 on Mondays to Saturdays and 07.00-24.00 on Sundays. Data for 3/10/95 on the East side of South Bridge have been removed.

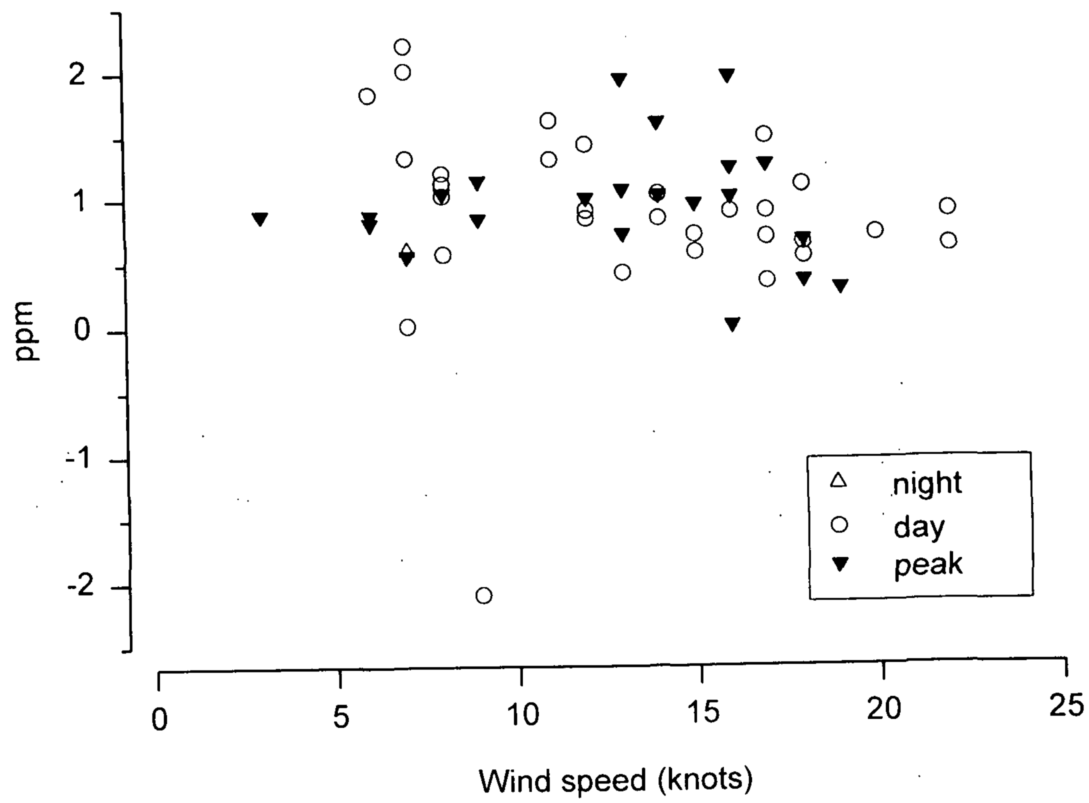



Figure 11: The relationship between the absolute difference in outdoor carbon monoxide concentrations measured on opposite sides of South Bridge (the concentration outside the cellar on the West minus the concentration outside the first floor on the East) and windspeed.

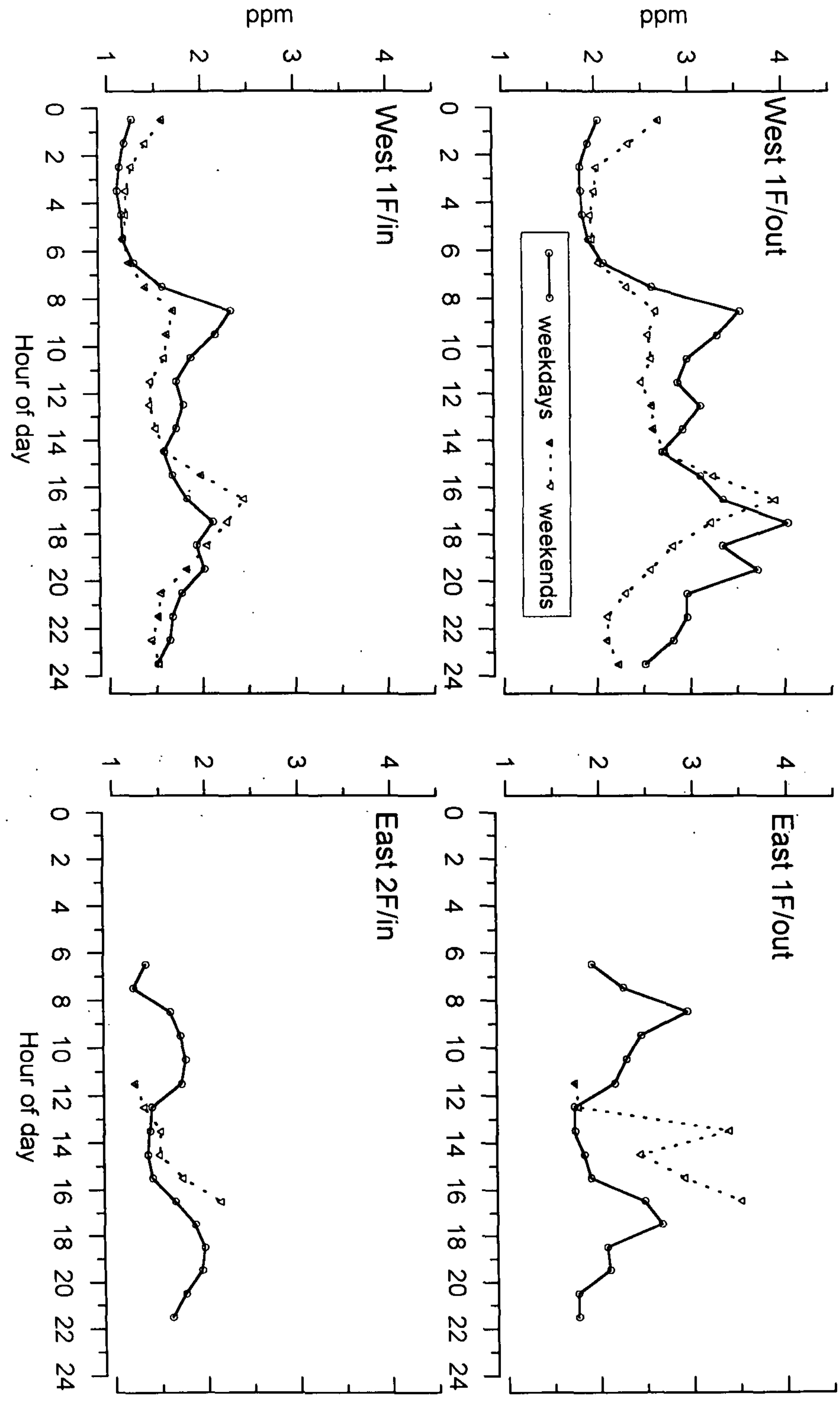



Figure 12: The mean diurnal variation in outdoor carbon monoxide concentrations measured in South Bridge; West 1F/out = outside cellar; West 1F/in = inside cellar; East 1F/out = outside first floor; East 2F/in = inside second floor office. Note that whereas the weekday means are based on 11 measurements, the weekend means are based on 2 or 3 measurements.

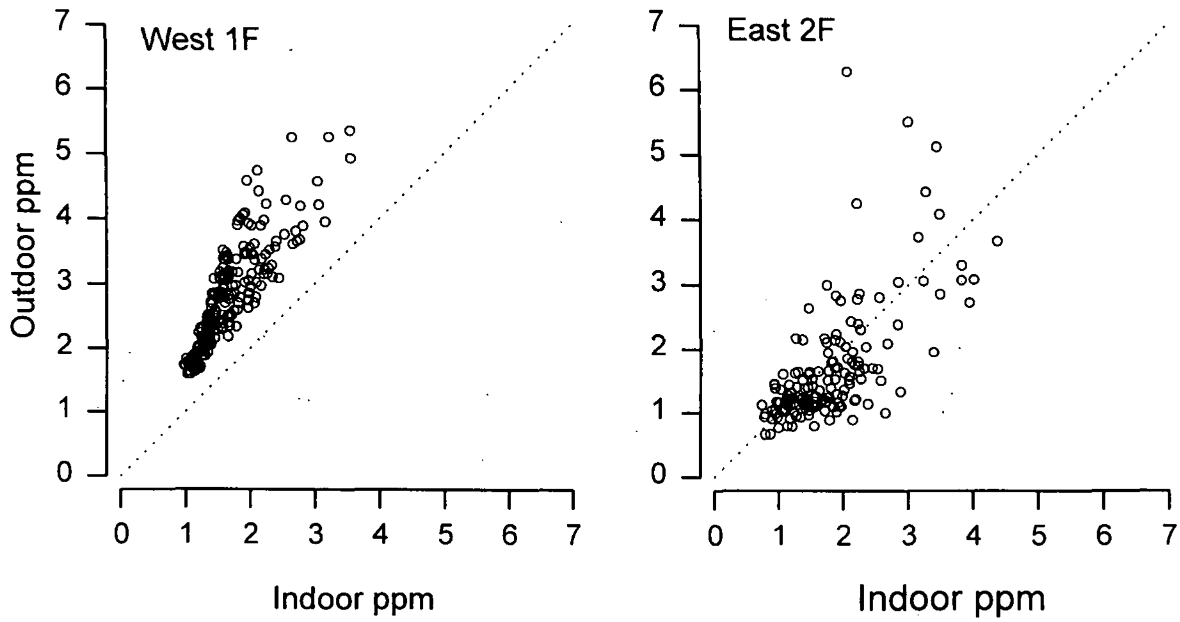



Figure 13: Relationships between indoor and outdoor measurements of carbon monoxide in South Bridge for the cellar (West 1F) on the West and the second floor office (East 2F) on the East. Dotted line represents the line of equality.

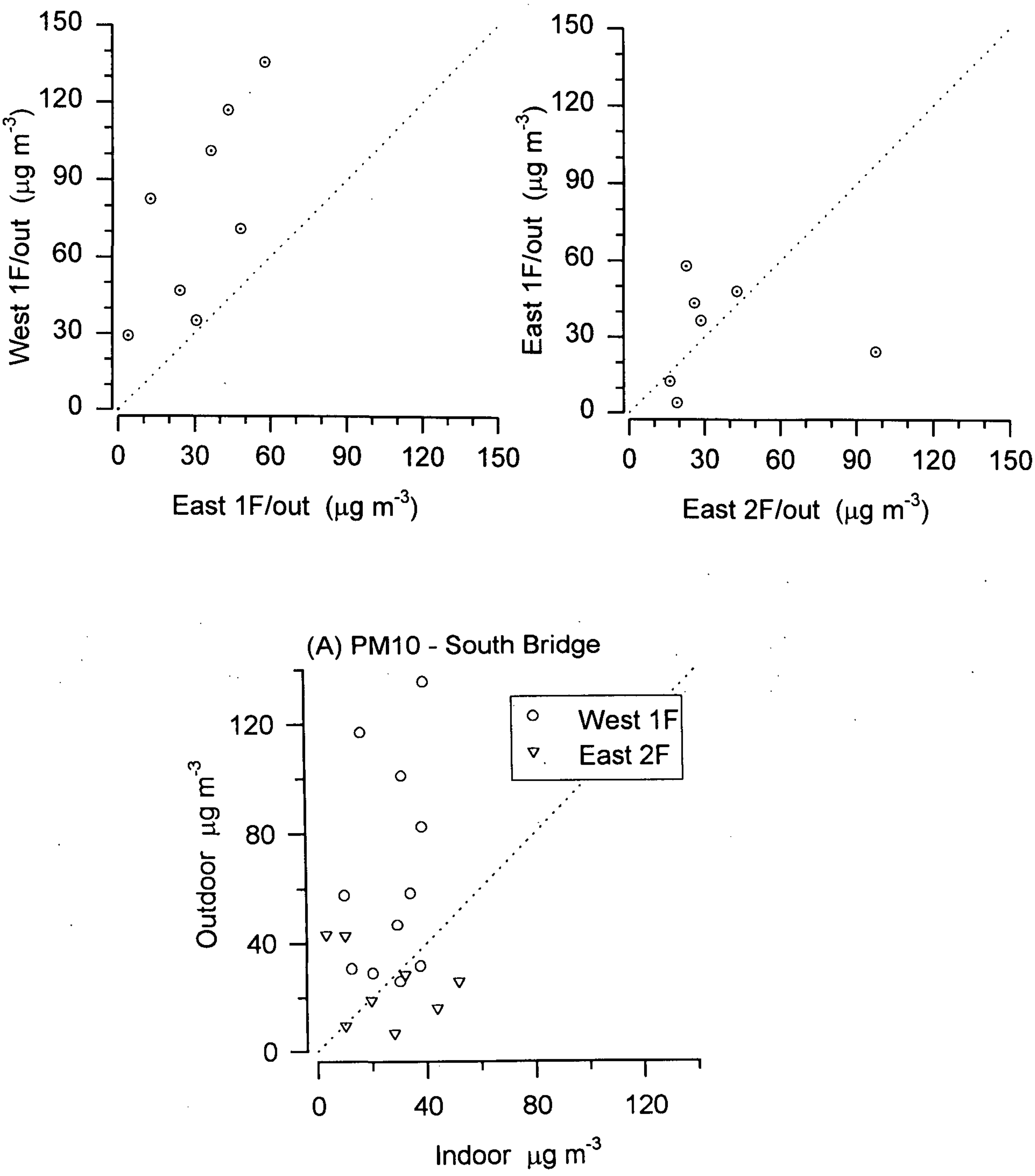



Figure 14: Relationships between outdoor particulate concentrations (PM10) measured on both sides of South Bridge (West 1F/out and East 1F/out), at different heights on the East side of South Bridge (1F = first floor; 2F = second floor) and between outdoor and indoor concentrations measured inside and outside the cellar on the West and the second floor office on the East.

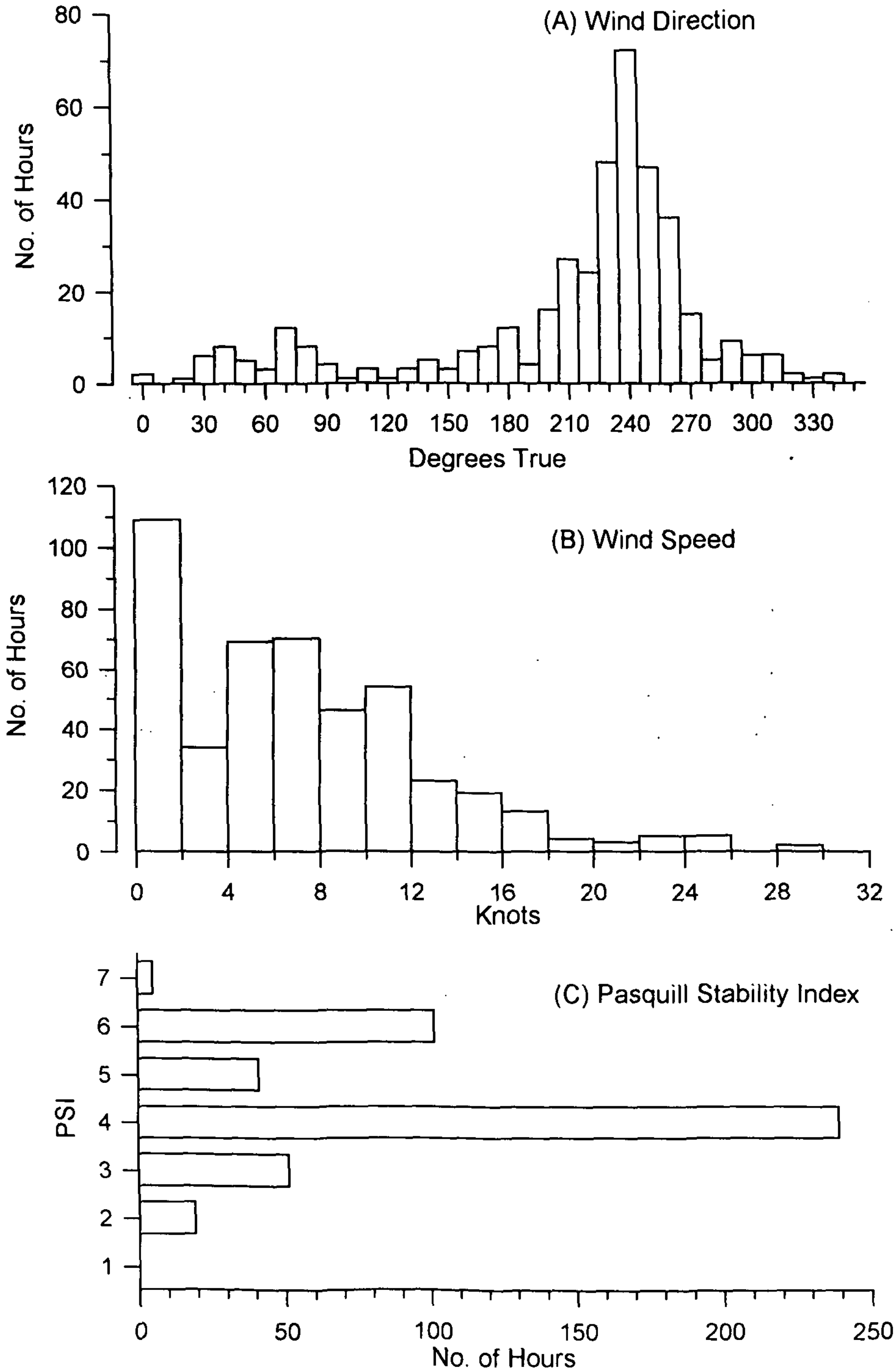



Figure 15: Summary of hourly weather conditions at Edinburgh Airport for the period covering the Frederick Street measurement campaign (28/9/95 to 11/10/95); a) wind direction data measured in degrees from true north b) windspeed data; c) hourly Pasquill Stability Index.

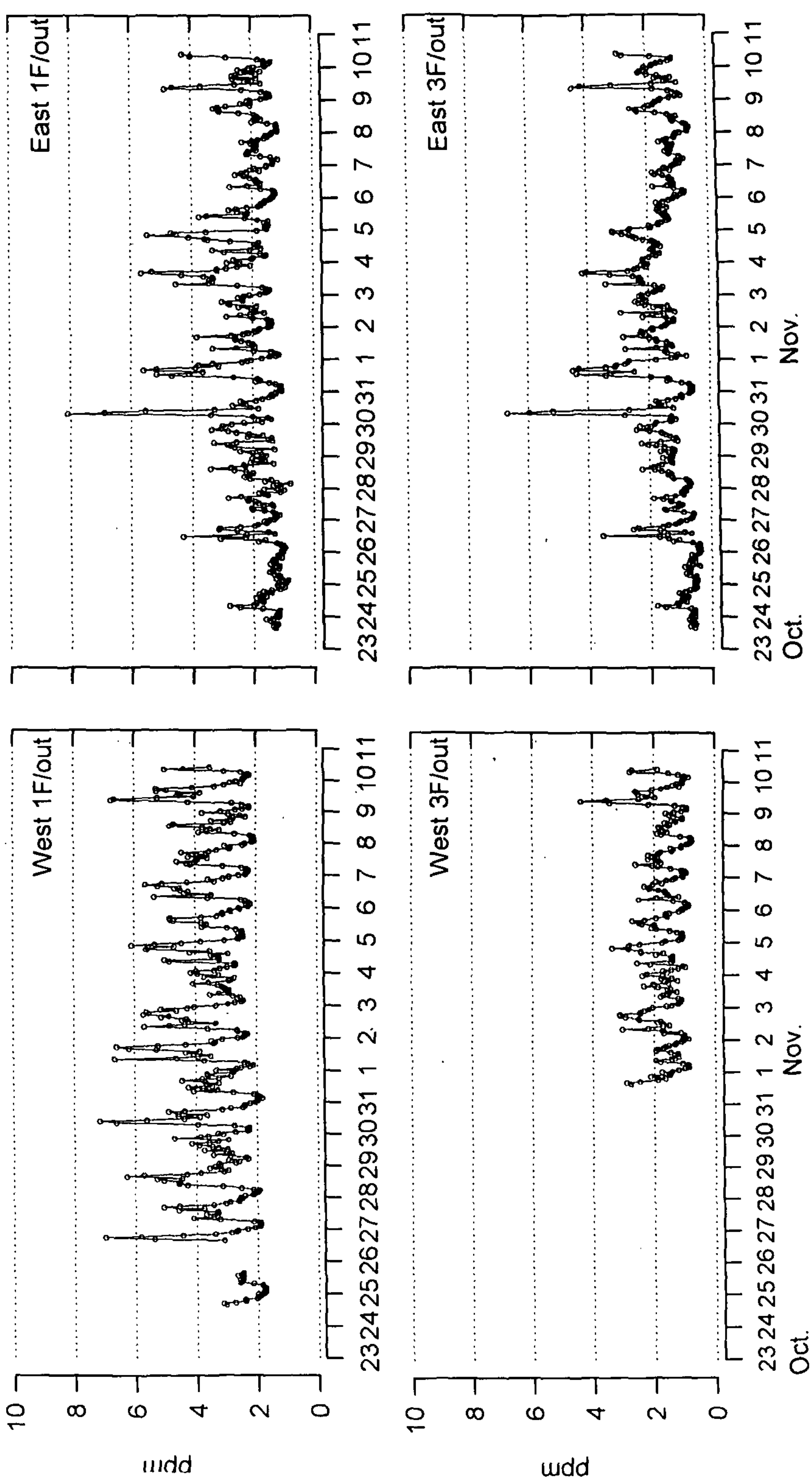
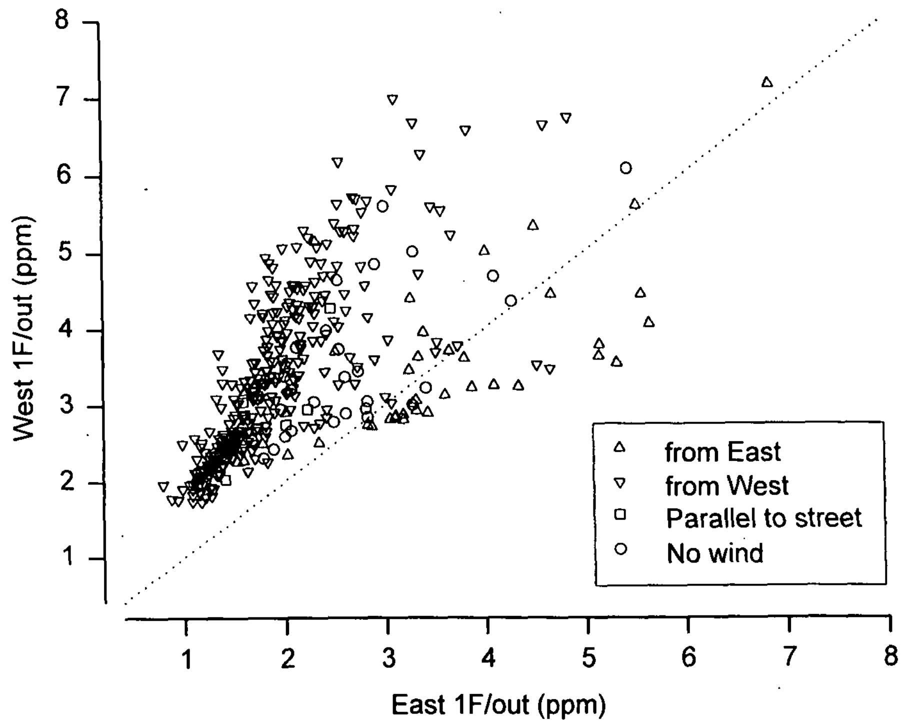



Figure 16: Time series plots of outdoor carbon monoxide concentrations during the measurement period (23/10/95-10/11/95) on the East and West sides of Frederick Street; 1F = first floor and 3F = third floor. The 29th October and 5th November were Sundays.



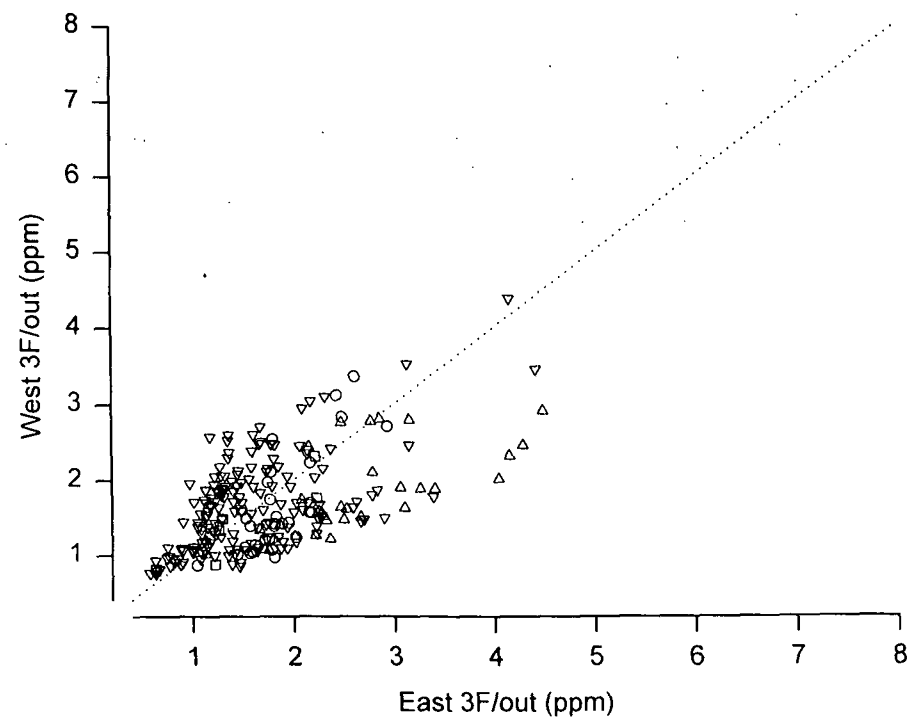




Figure 17: Relationships between hourly outdoor carbon monoxide concentrations measured at different heights on the east and west sides of Frederick Street (1F - first floor, 3F - third floor). Dotted line represents the line of equality.

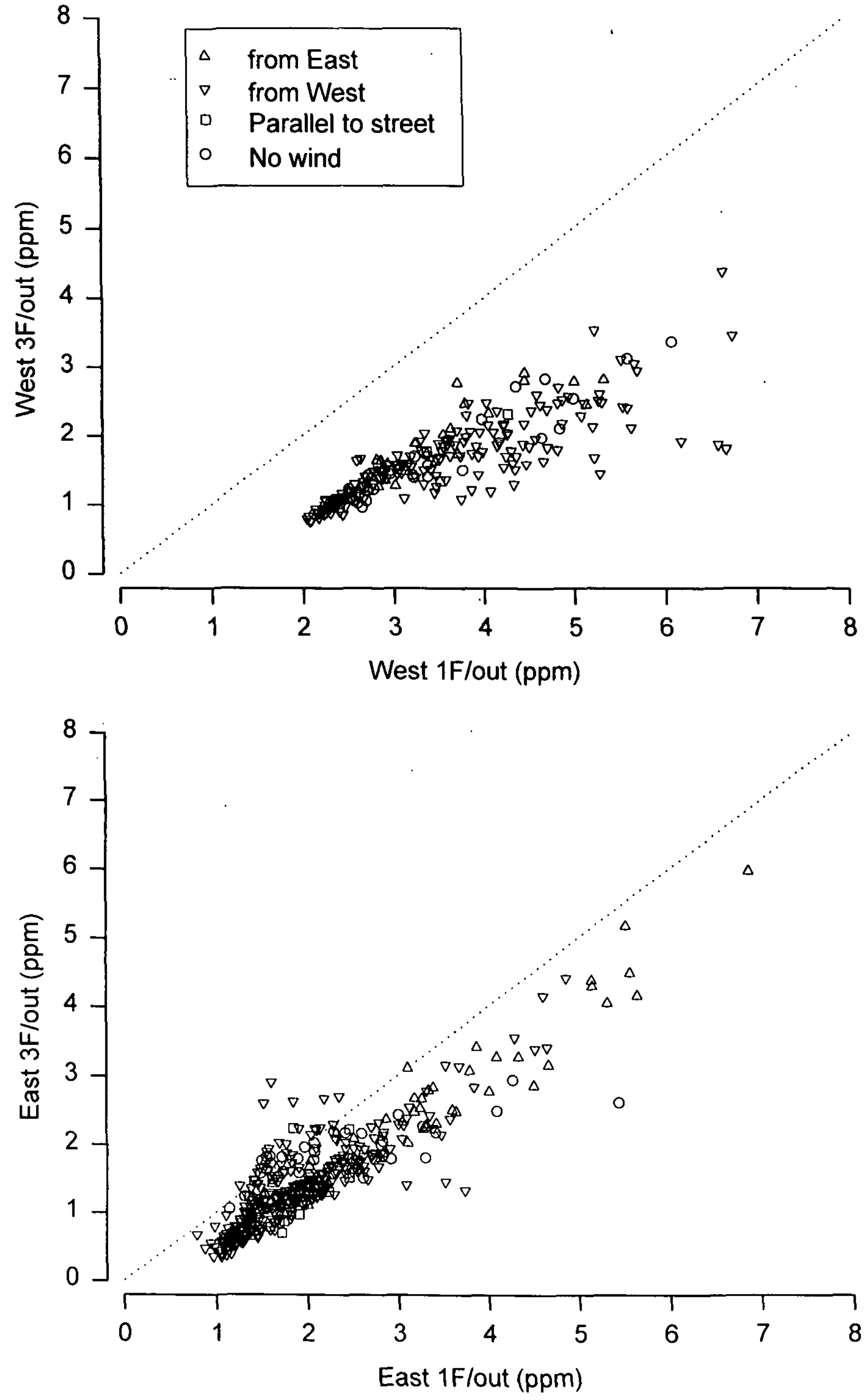



Figure 18: Relationships between hourly outdoor carbon monoxide concentrations measured on either side of Frederick Street at first floor level (1F) and third floor level (3F). Dotted line represents the line of equality.

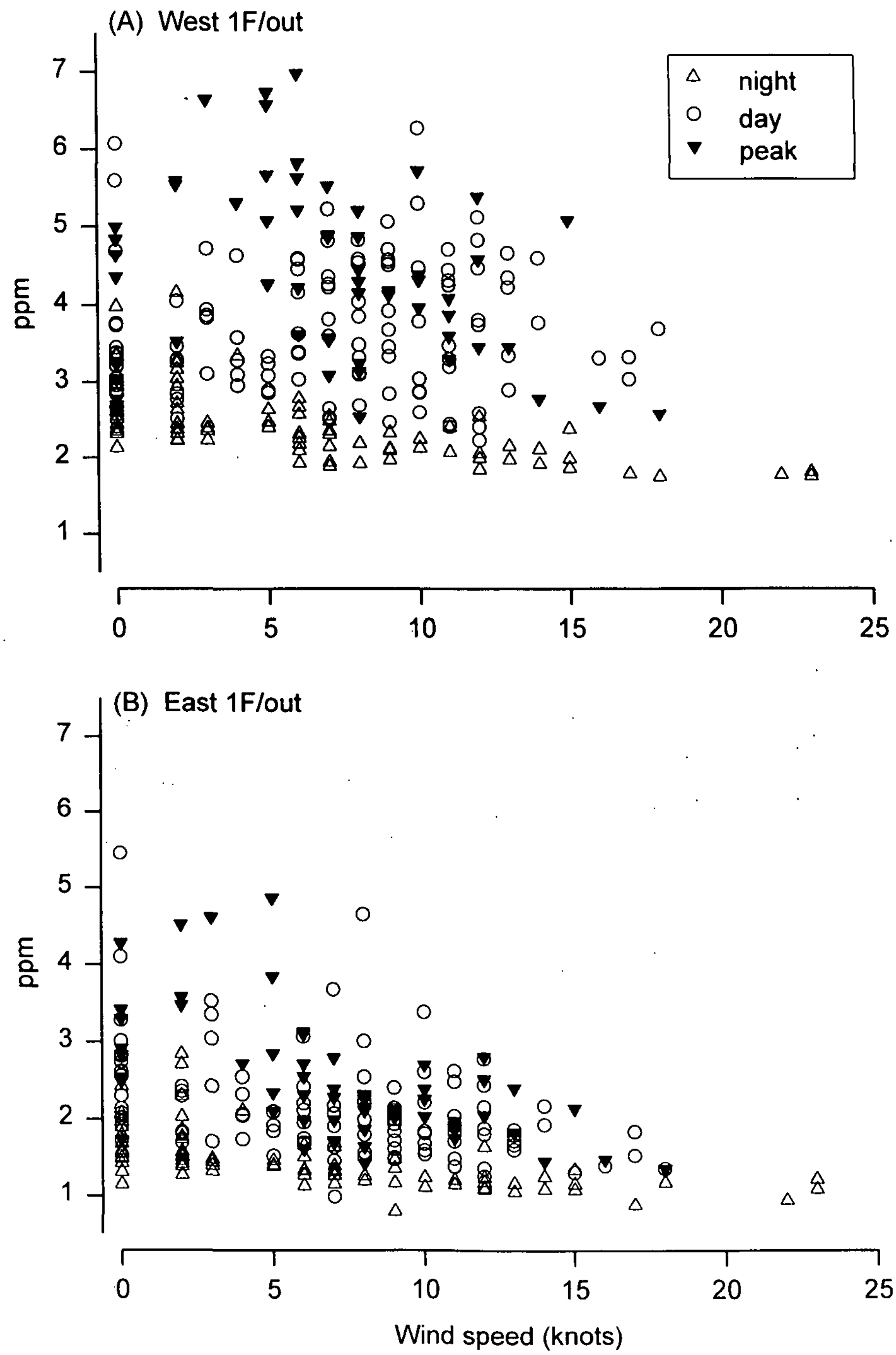



Figure 19: Relationship between the hourly outdoor carbon monoxide concentrations measured in Frederick Street and windspeed labelled by time of day. Night is defined as 00.00 to 07.00, peak times are defined as the periods 07.00 to 10.00 and 16.00 to 19.00 on all days excluding Sundays and day covers all remaining time: 10.00-16.00 and 19.00-24.00 on Mondays to Saturdays and 07.00-24.00 on Sundays.

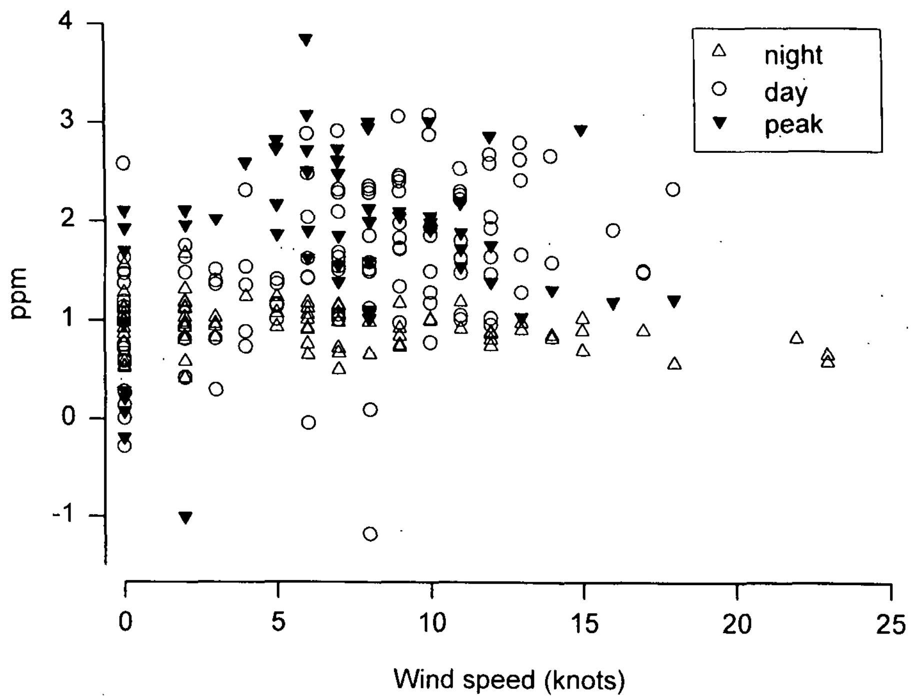



Figure 20: Relationship between the absolute difference in hourly outdoor carbon monoxide concentrations measured on the two sides of Frederick Street and windspeed (concentration at first floor level on the West side of the street minus that at first floor level on the East).

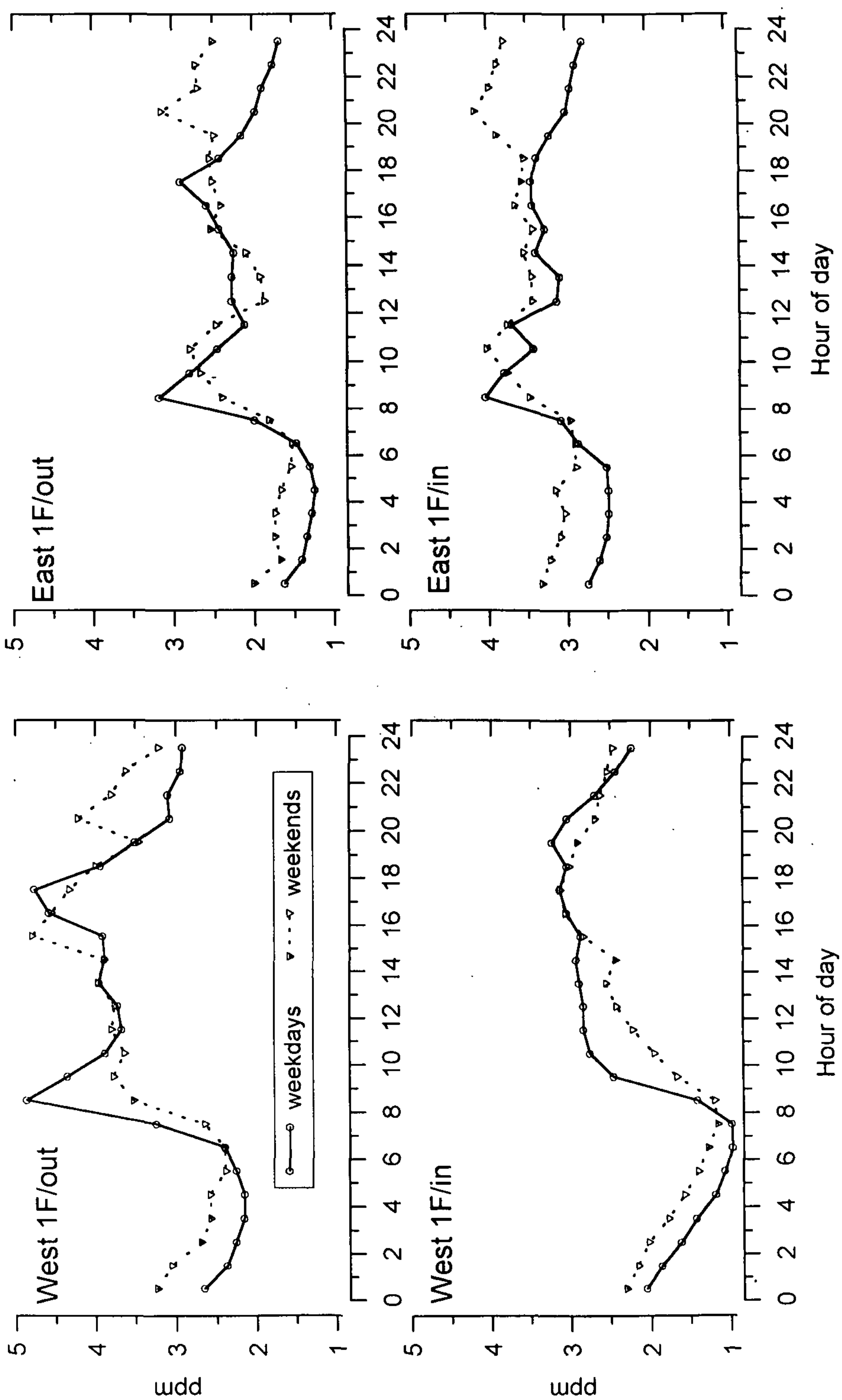



Figure 21: The mean diurnal variation in carbon monoxide concentrations measured on the West and East sides of Frederick Street; 1F/out - outside first floor level, 1F/in - inside at first floor level. Note that whereas the weekday means are based on 12 measurements, the weekend means (Saturday+Sunday) are based on measurements made over 2 weekends.

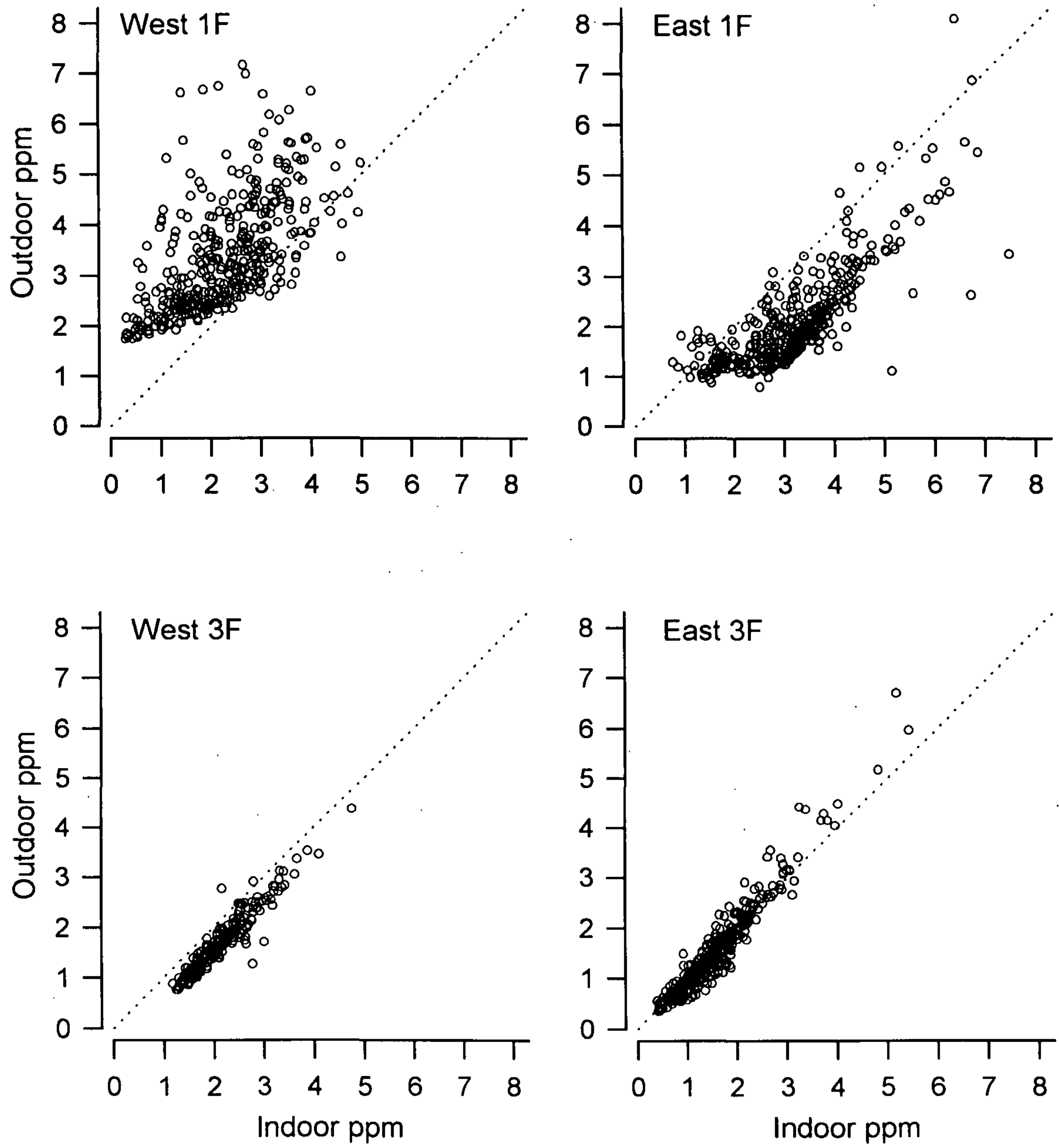
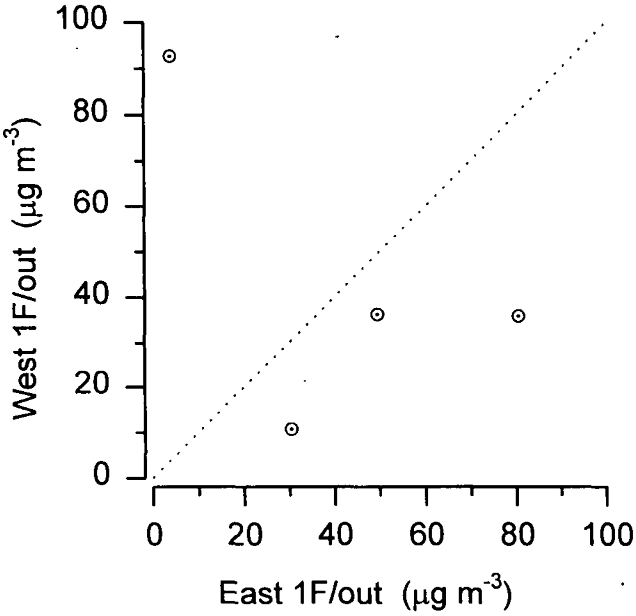



Figure 22: Relationships between indoor and outdoor hourly measurements concentrations of carbon monoxide measured in Frederick Street. Dotted line represents the line of equality.



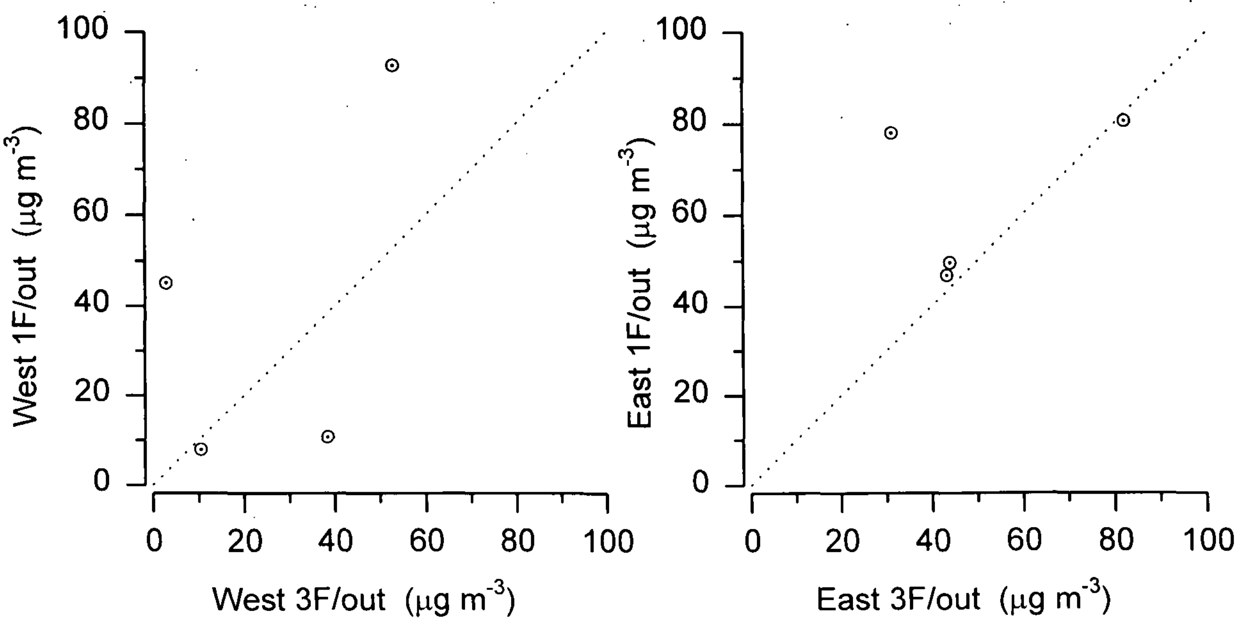




Figure 23: Relationships between outdoor particulate concentrations (PM10) measured on both sides of Frederick Street and at different heights above Frederick Street. Measurements include both 24 hour means (weekdays) and 72 hour means (weekends). Dotted line represents the line of equality.

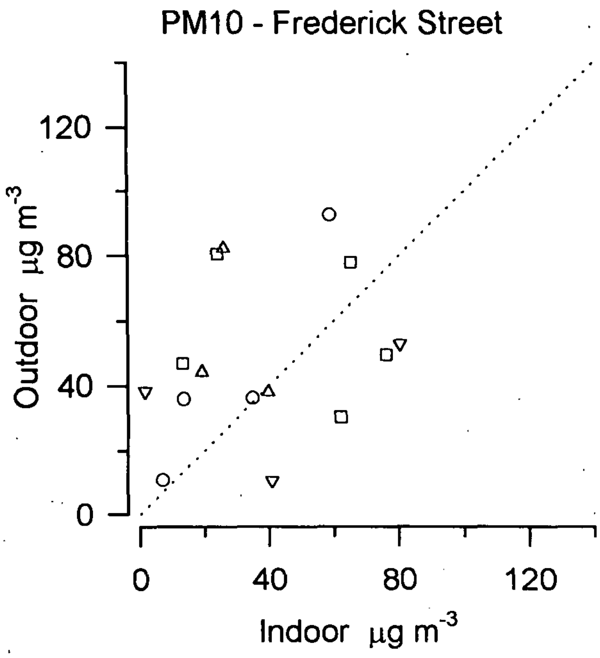



Figure 24: Relationship between indoor and outdoor particulate concentrations (PM10) in Frederick Street (1F - first floor; 3F -third floor).

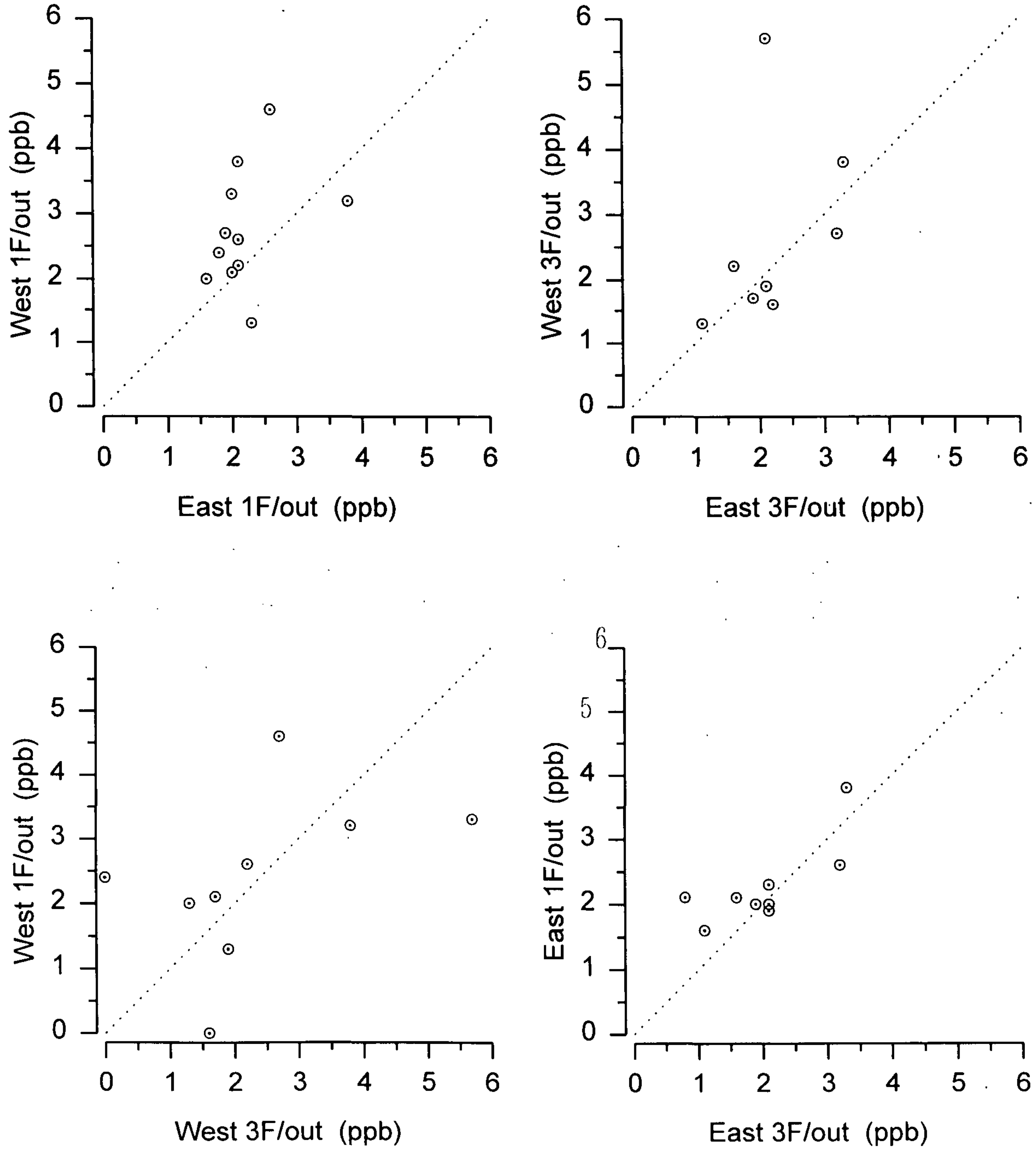



Figure 25: Relationships between outdoor benzene concentrations measured on opposite sides of Frederick Street and at different heights above Frederick Street (1F- first floor; 3F - third floor). Measurements include both 24 hour means (weekdays) and 72 hour means (weekends). Dotted line represents the line of equality.

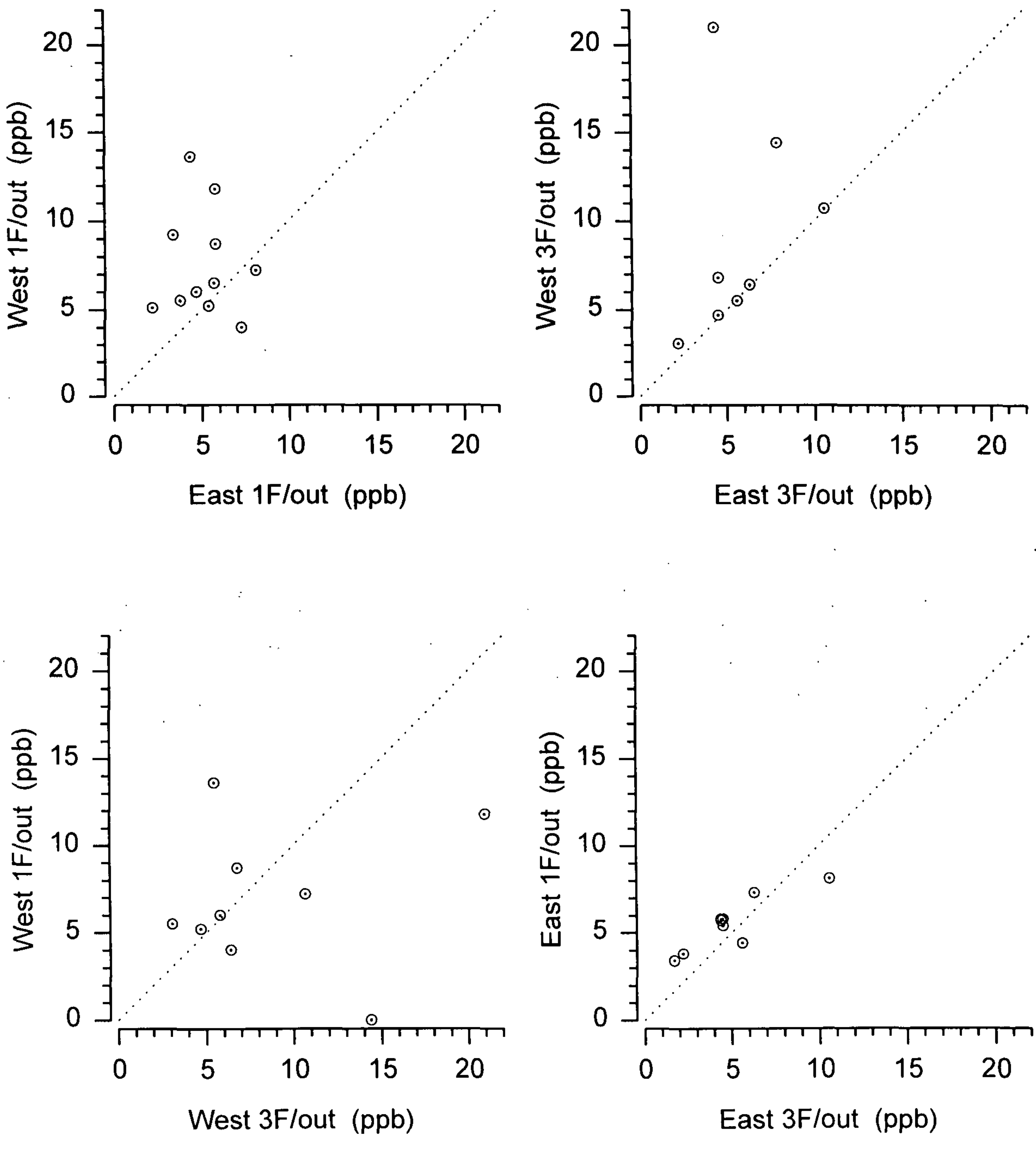



Figure 26: Relationships between outdoor toluene concentrations measured on opposite sides of Frederick Street and at different heights above Frederick Street (1F- first floor; 3F - third floor). Measurements include both 24 hour means (weekdays) and 72 hour means (weekends). Dotted line represents the line of equality.

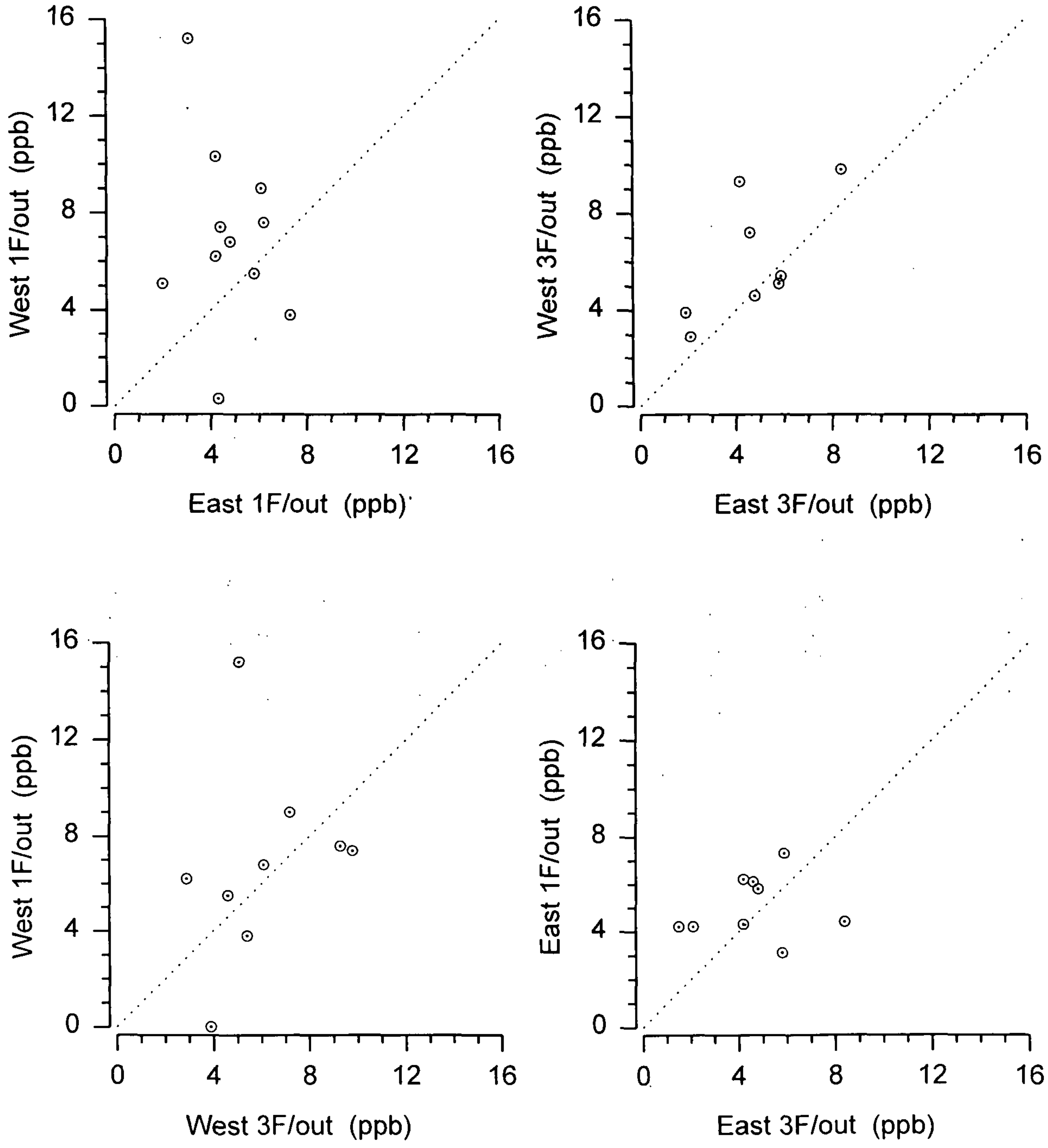



Figure 27: Relationships between outdoor xylene concentrations measured on opposite sides of Frederick Street and at different heights above Frederick Street (1F- first floor; 3F - third floor). Measurements include both 24 hour means (weekdays) and 72 hour means (weekends). Dotted line represents the line of equality.

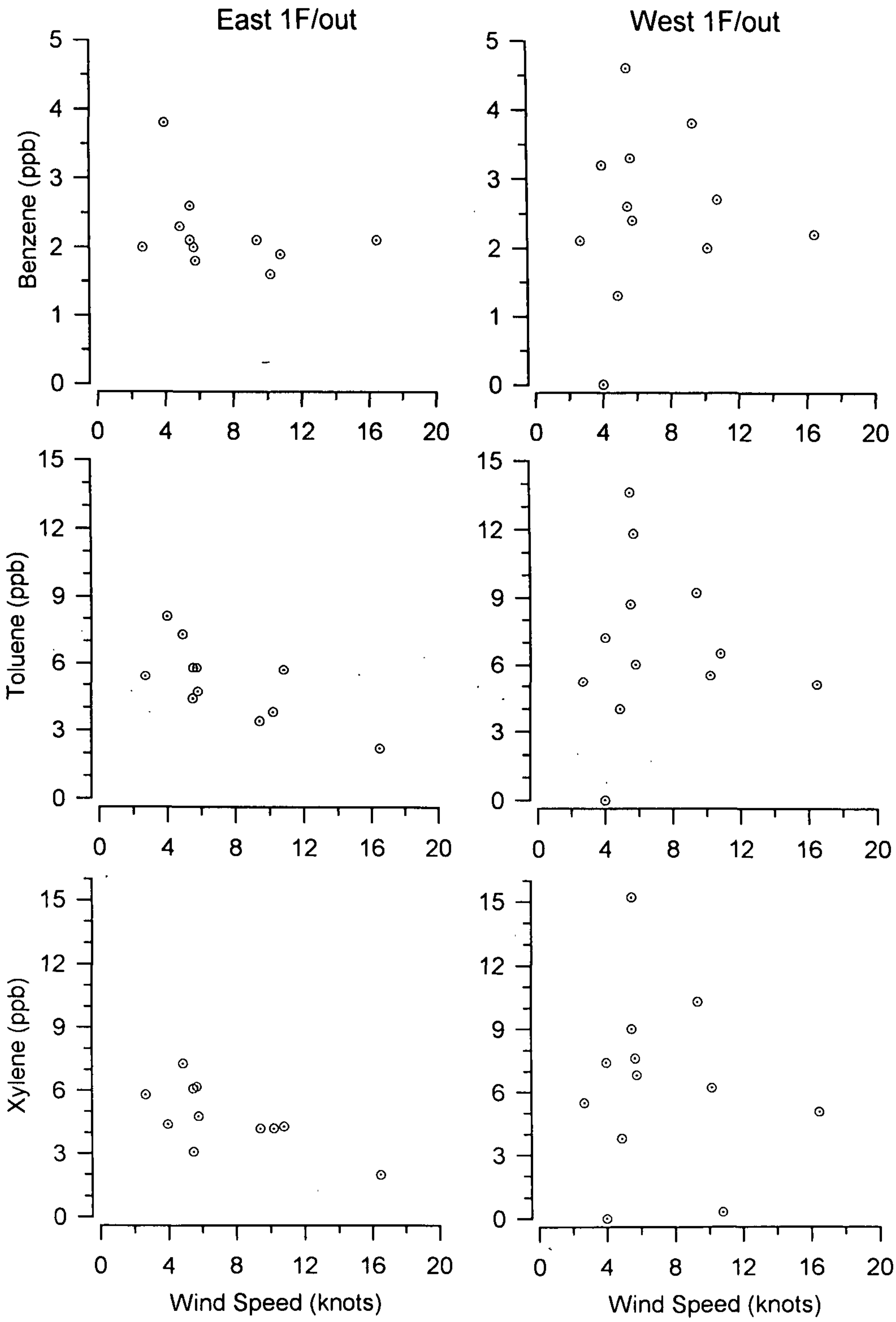



Figure 28: Relationships between outdoor concentrations of benzene, toluene and xylene at first floor level on both sides of Frederick Street and mean windspeed over the same 24 and 72 hour measurement periods.

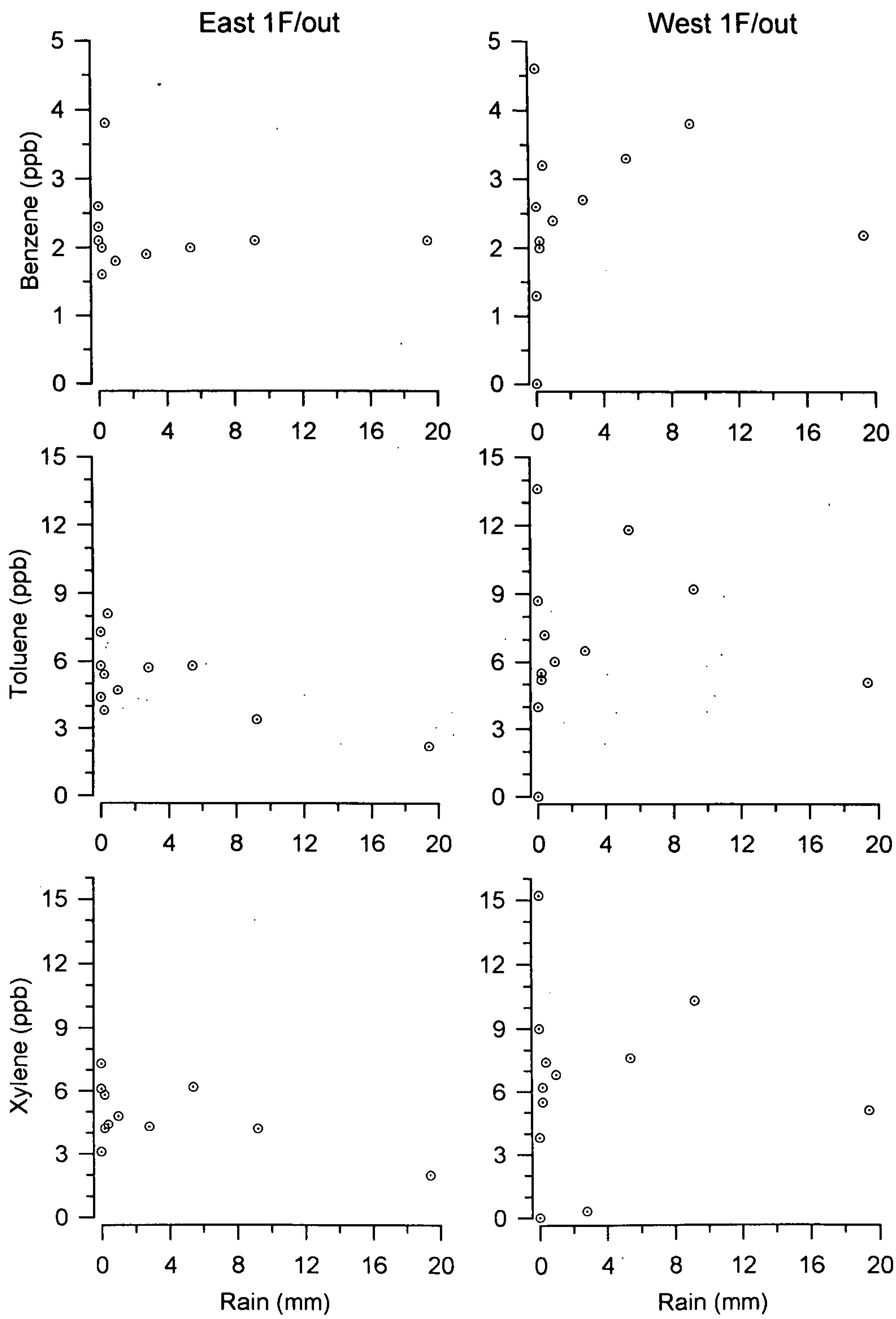



Figure 29: Relationships between outdoor concentrations of benzene, toluene and xylene at first floor level on both sides of Frederick Street and daily rainfall.

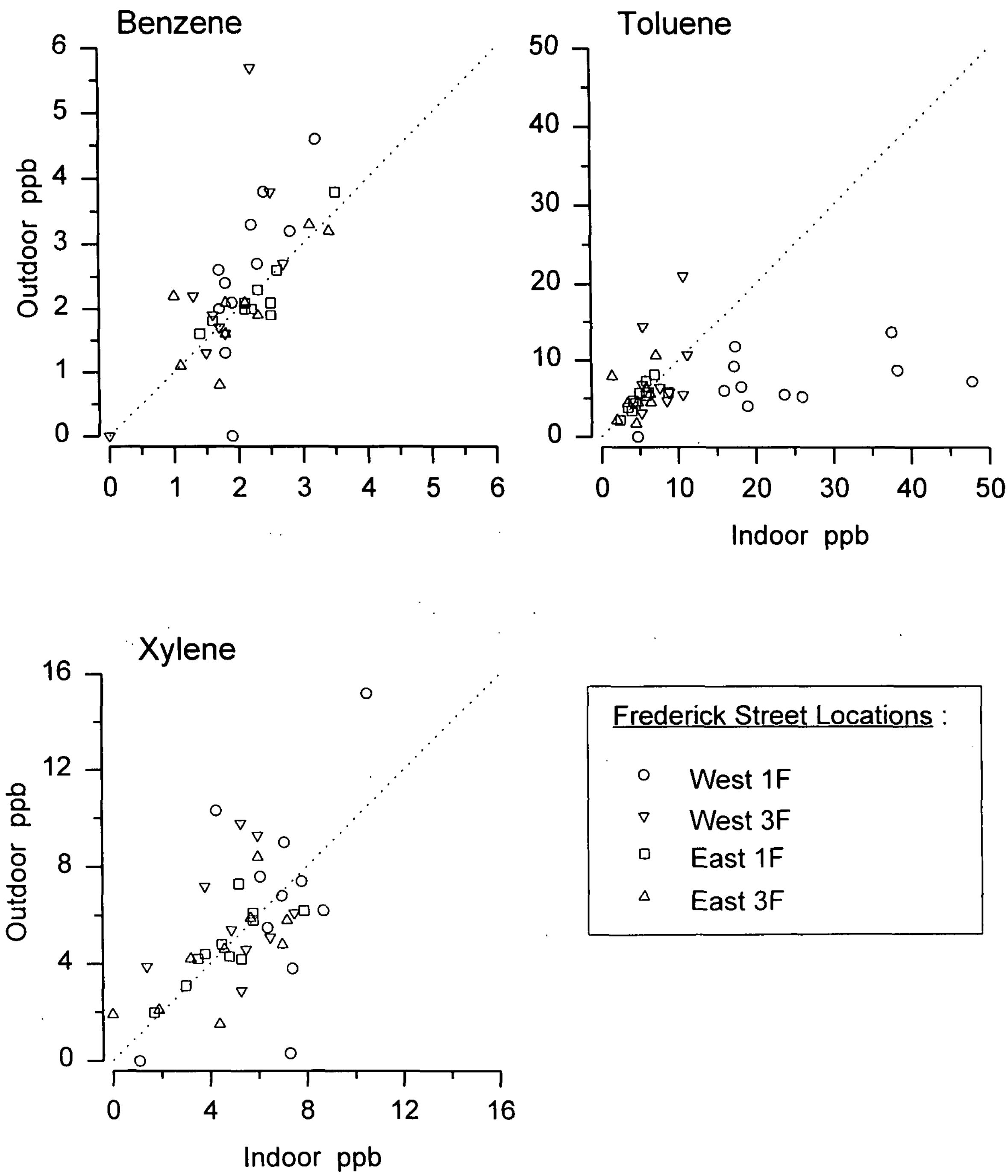



Figure 30: Relationships between indoor and outdoor concentrations of benzene, toluene and xylene measured in Frederick Street.

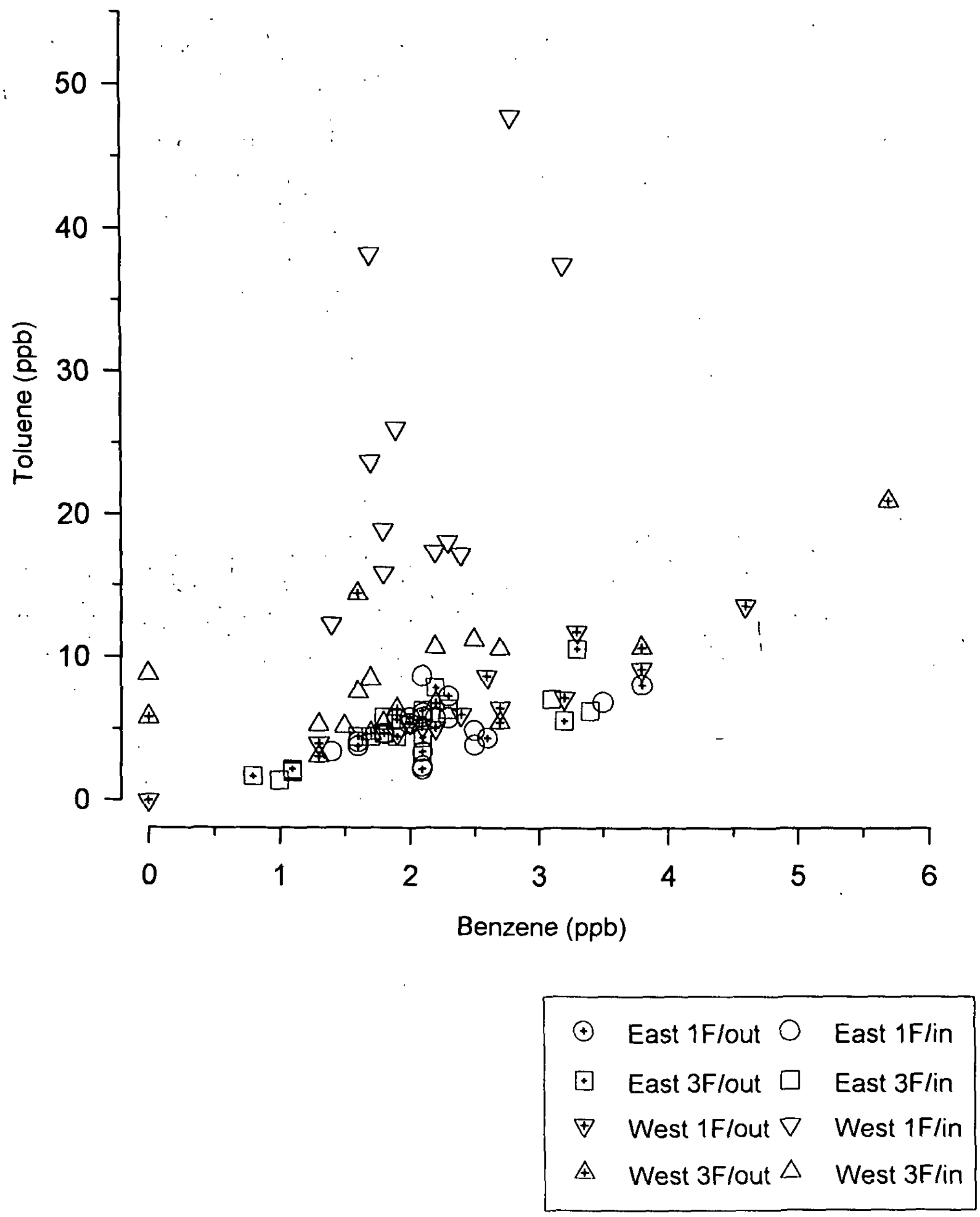



Figure 31: Relationships between benzene and toluene concentrations measured both indoors (in) and outside (out) at first and third floor level on both sides of Frederick Street.

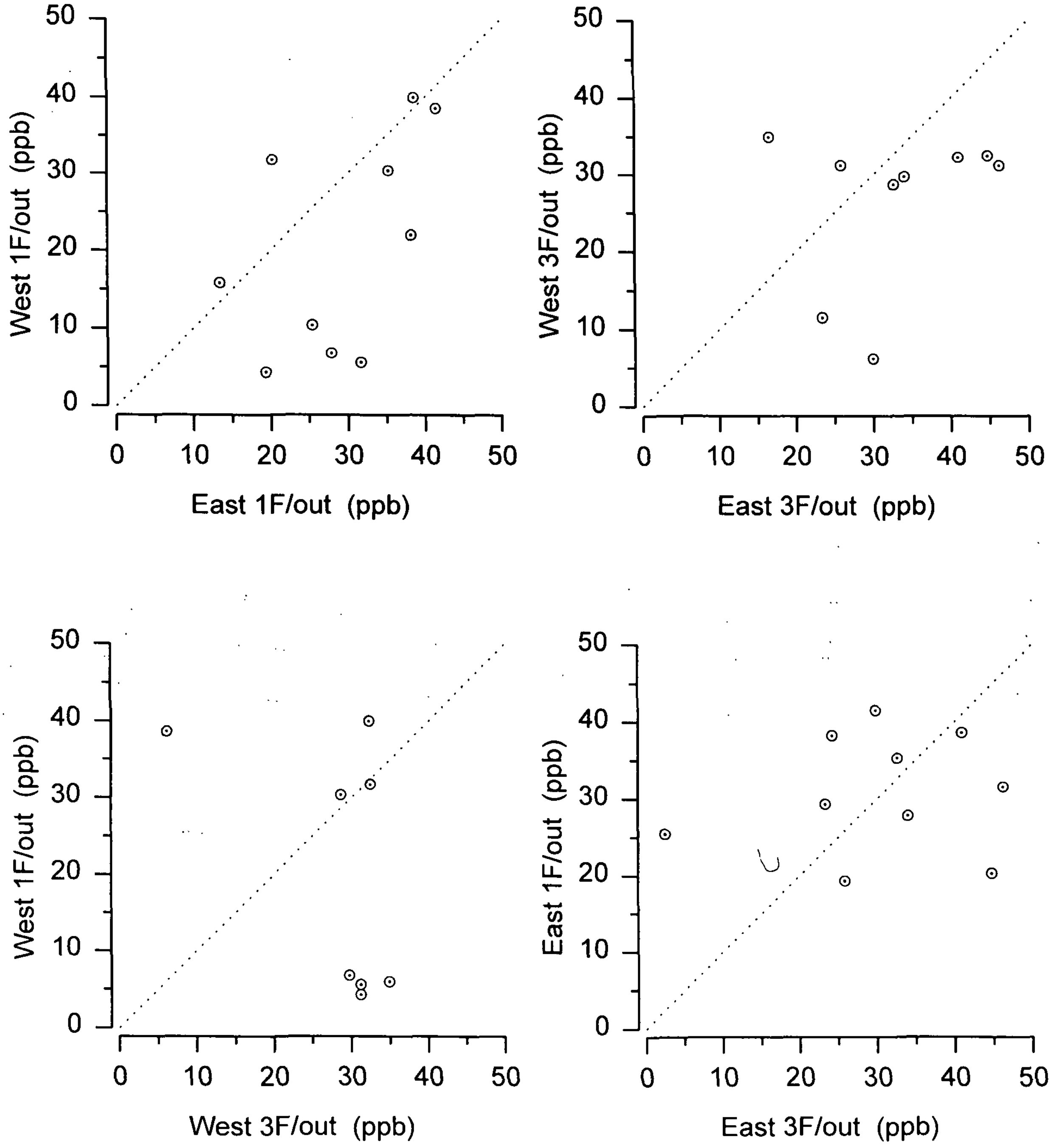



Figure 32: Relationships between outdoor nitrogen dioxide concentrations measured on both sides of Frederick Street and at different heights (first and third floor level) above Frederick Street. Measurements include both 24 hour means (weekdays) and 72 hour means (weekends). Dotted line represents the line of equality.

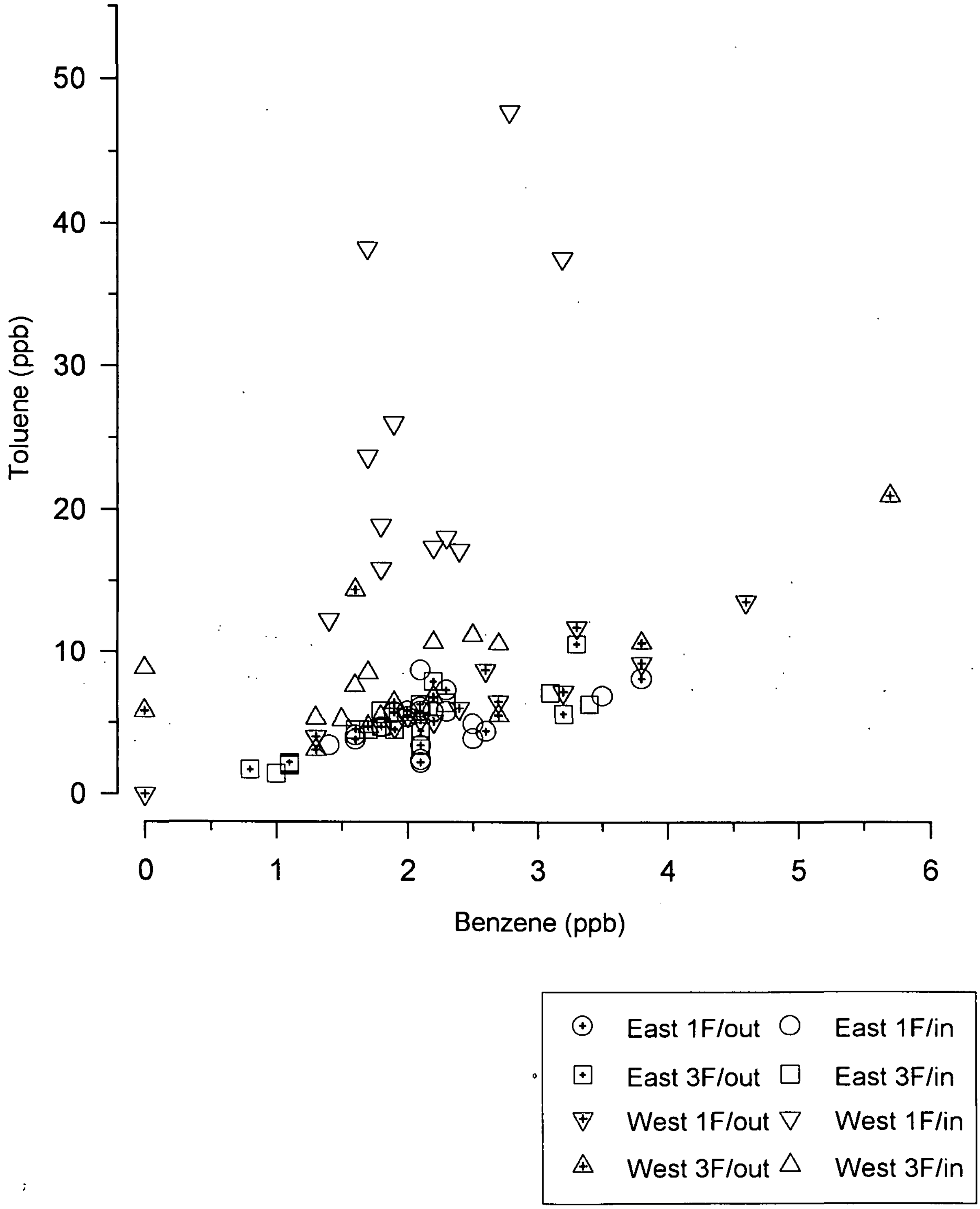



Figure 33: Relationships between outdoor nitrogen dioxide concentrations measured in Frederick Street and rainfall and mean windspeed over the same 24 and 72 hour measurement periods.

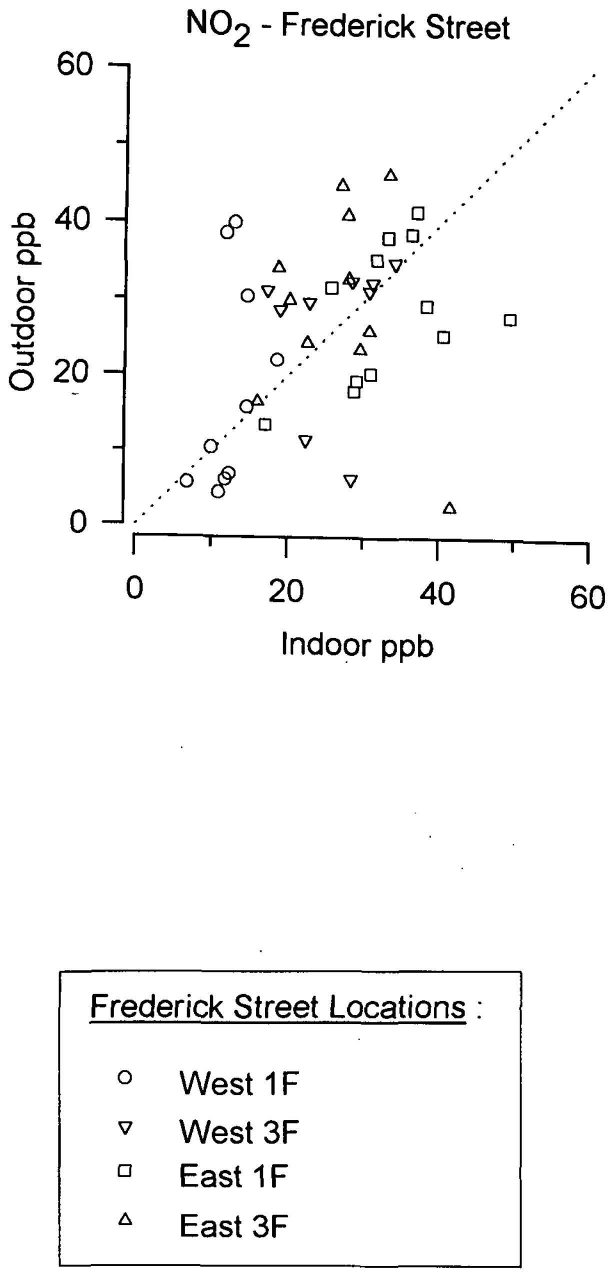



Figure 34: Relationship between indoor and outdoor nitrogen dioxide concentrations measured in Frederick Street.

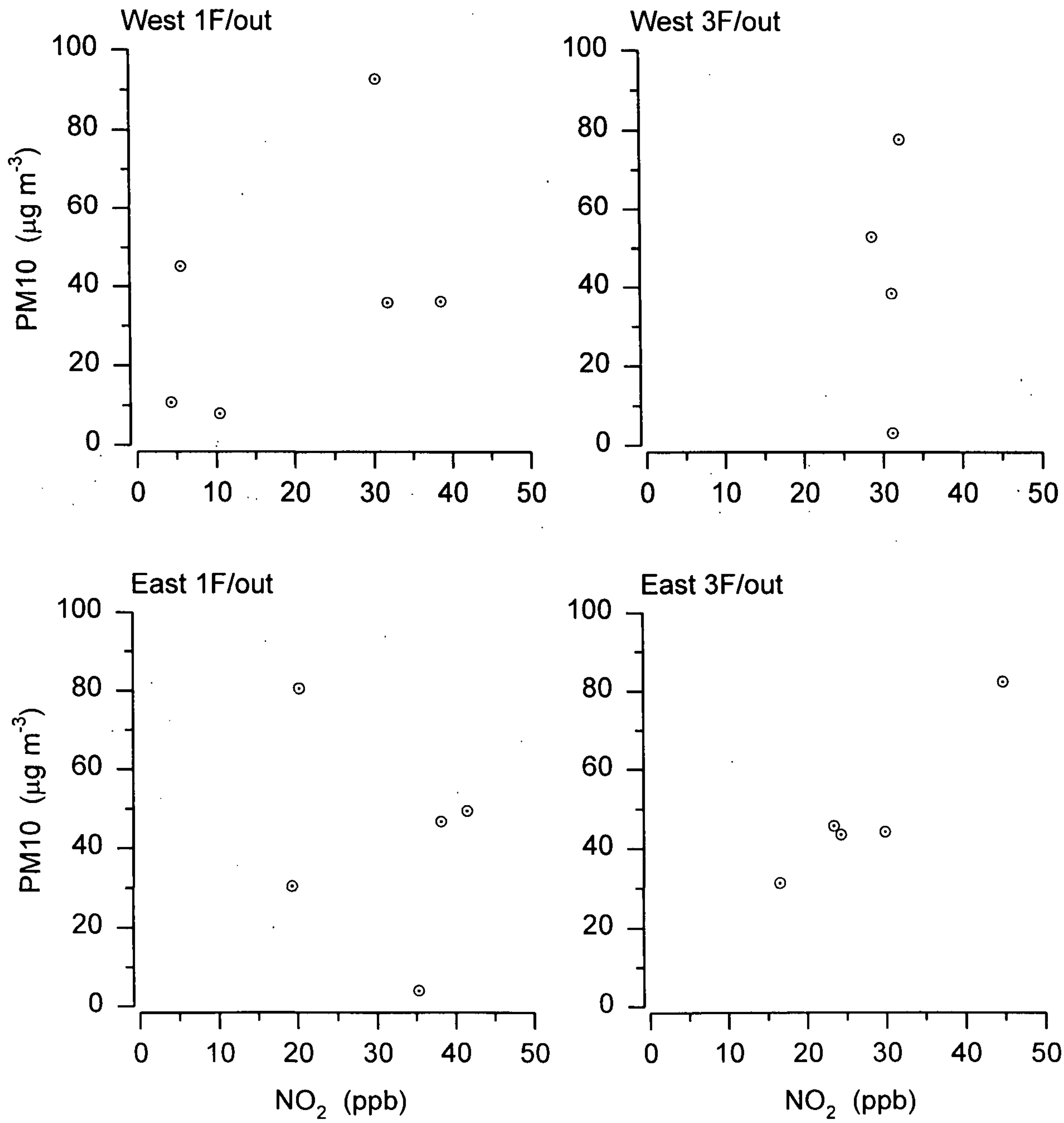



Figure 35: Relationships between outdoor particulate (PM10) and nitrogen dioxide concentrations measured in Frederick Street.

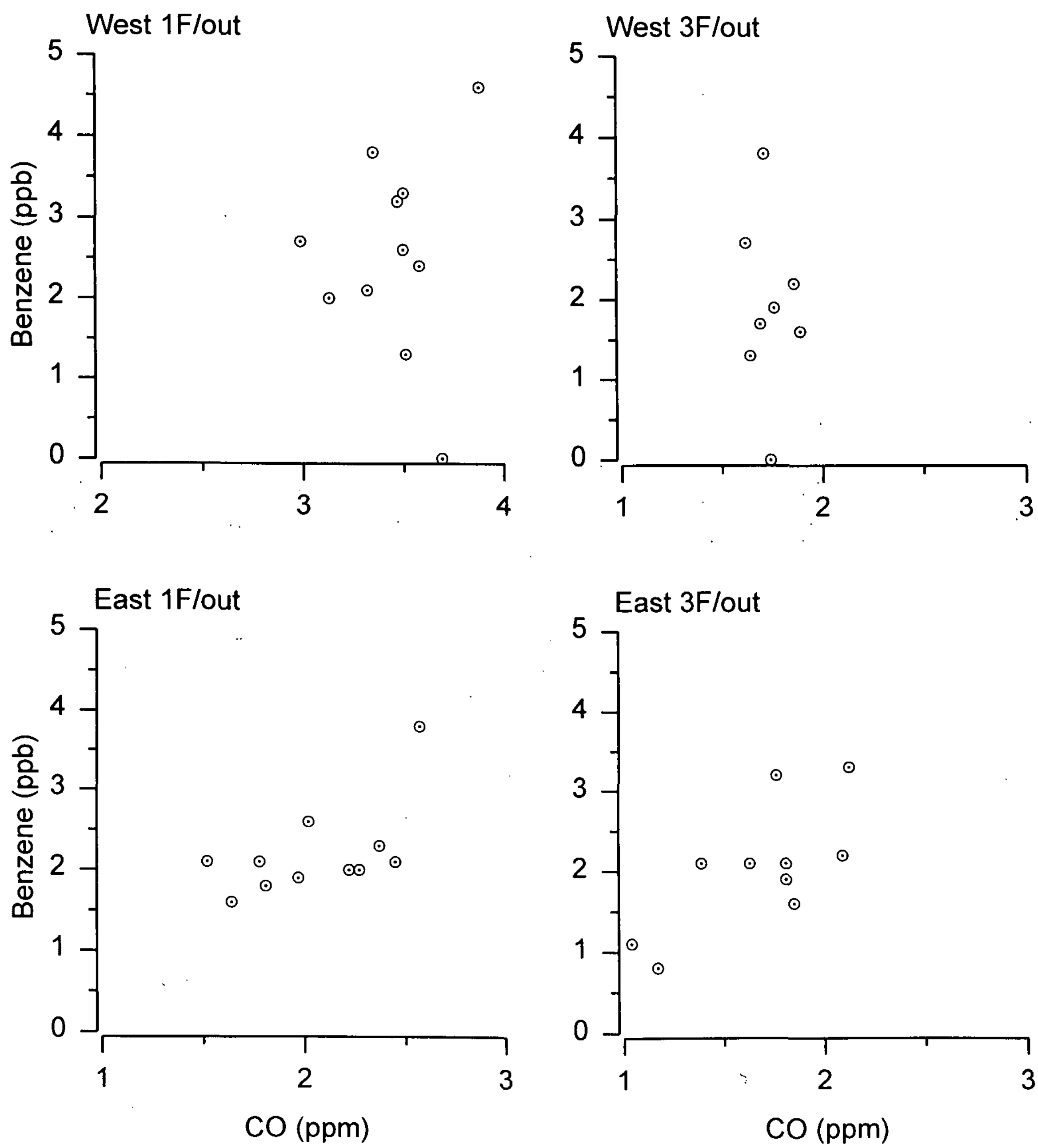



Figure 36: Relationships between outdoor benzene concentrations and mean carbon monoxide concentrations for the same 24 and 72 hour measurement periods in Frederick Street.

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