THE METEOROLOGY AND CLIMATOLOGY OF AIR POLLUTION IN WEST CENTRAL SCOTLAND

A Thesis presented for the Degree of
Doctor of Philosophy of the University
of Glasgow

by

JOHN C. SWEENEY

Department of Geography,
University of Glasgow,
Glasgow.

1980

TO MY PARENTS

PREFACE

In recent decades the age old problem of air pollution has assumed a new importance as evidence has become available concerning its adverse effects both on a local and global scale. Awareness of these effects has been most marked in densely populated industrialised countries where the juxtaposition of people and their employment makes 'living with air pollution' a necessary, though unwelcome reality. In most of these areas some form of written or unwritten guidelines have evolved which express a consensus compromise between the adverse effects of air pollution on the one hand and the material prosperity accompanying industrialisation on the other. Increasingly, internationally established criteria are being utilised as a basis for managing air quality within a region, and for assessing the impact of planned new sources within it.

Such an approach implies that the effect of a new or existing source is readily quantifiable in terms of its impact on ground level concentrations. This is not the case and was demonstrated by previous workers with reference to the changing industrial landscape of West Central Scotland. Environmental impact analyses in relation to proposed new high level sources in the Clyde Estuary were seen to be inconclusive. This was attributed to a gap in knowledge concerning the interaction of topographical and meteorological influences on pollution dispersal within the region.

The following study is essentially a response to the need acknowledged above. It seeks to investigate in detail various meteorological and climatological factors which, acting within the topographical make up of West Central Scotland, encourage or restrict the dispersal of emissions from existing or planned pollutant sources. Such an understanding, though developed for a unique location, will inevitably have a contribution to make in relation to similar problems in other areas.

Basically then two objectives can be noted, one academic, the other applied. The first aim is to examine the role of atmospheric factors in enhancing ground level concentrations of smoke and sulphur dioxide in the region, and the second is to illustrate the utility of such data in air quality management schemes.

ACKNOWLEDGEMENTS

I would like to express my gratitude to several workers who, acting individually or on behalf of various organisations, have rendered invaluable assistance in the preparation of this thesis.

On an academic level a primary obligation must be recognised to Emeritus Professor Ronald Miller and Professor Ian B. Thompson for permitting me to pursue post graduate research in the Department of Geography, University of Glasgow from 1975 to 1978. For the period since then thanks are also extended to Professor William J. Smyth for permitting completion of the work at St. Patrick's College, Maynooth.

Establishing and maintaining the thermohygrograph network involved co-operation from several bodies to whom I would like to express my thanks. These include officials of the Planning Department Renfrew District Council, the Water Department of Strathclyde Regional Council, and the Senior Meteorological Officer, Glasgow Airport. Thanks are also due to Captain P.R. Byrd, Commanding Officer, U.S. Naval Communication Station, Londonderry for security concessions granted in respect of the Gleniffer thermohygrograph installation.

Data was made available by officials of the Environmental Health Departments of Glasgow, Paisley and Inverclyde Districts and by Mr. Harry McKellar of Glasgow Weather Centre, just prior to his recent retirement. Assistance in computer programming must also be acknowledged from Mr. Graham Reid of the Planning Department Strathclyde Regional Council, who was also responsible for devising several of the programmes utilised in the earlier part of the study. Permission to reproduce Plate 2 must also be acknowledged from the Rev. James McGreehin.

Mention must also be made of the invaluable assistance of two members of the Geography Department: Maria Cunningham and Cathie Gunn. As is quite clear, their secretarial and cartographical skills are of the highest calibre, but also their patience and endurance in what must have seemed an endless profusion of graphs and Greek letters was most encouraging.

Finally I am indebted to my supervisor, Cyril Halstead, Senior Lecturer in Geography, University of Glasgow, without whose constant encouragement this study would never have come to fruition. His extensive expertise in the fields of climatology and meteorology is matched only by his incisive and imaginative approach to academic research. Studying under him has been both a privilege and an intensely enriching experience.

TABLE OF CONTENTS

Page

ABSTRACT

Despite considerable amelioration in ground level concentrations of smoke and sulphur dioxide in West Central Scotland in the last two decades, high pollution episodes still occur on occasion, and high winter averages of SO_2 still characterise parts of the conurbation. For these reasons a continuing monitoring programme remains essential, largely as a means of projecting and assessing the impact of new high level sources on both the Clyde and Forth Estuaries. In relation to these, however, classical dispersion models and formulae have not been found to be as effective as anticipated, largely because of their failure to accommodate the interaction of the relief characteristics of the area with several aspects of its meteorological environment, most notably inversions of temperature in the lower atmospheric levels.

Evidence from fieldwork and from extensive analysis of radiosonde data suggests that such inversions are fairly frequent occurrences in the Glasgow Basin and can often prove persistent, lasting several days in some cases. In such circumstances effluent emitted within the Basin may be trapped, giving rise to enhanced ground level concentrations, and in extreme cases to the pollution episodes characteristic of the area in the past. Detailed examination of these features enabled conclusions concerning their likely occurrence, duration, altitude and behaviour to be drawn. In a wider perspective the inversion climatology of West Central Scotland was compared with other areas and was found to reflect large scale synoptic controls. On a more practical level however it was envisaged incorporating such inversion data into future dispersal modelling calculations.

Of more immediate significance as far as West Central Scotland was concerned was the discovery that the effectiveness of these pollution lids varied considerably with altitude, being most effective at particular height categories below 1500 metres. These categories were found to relate to previously identified erosion terraces in the Clyde Basin and beyond. Their influence was in turn shown to vary with

other aspects of the meteorological environment, most notably wind speed, with a progression of effective influences from local to more wide ranging in association with increasing wind speed. Other relief influences were also apparent in restricting the dispersal of power station emissions from Eastern Scotland with clear evidence of funnelling through gaps in the hills surrounding the Glasgow Basin.

Periods of enhanced pollution were most common during winter fogs. The fieldwork records here suggested that air movement was the most important aspect in causing and maintaining such fogs, rather than the radiational considerations advanced in classical interpretations. Katabatic winds were observed which appeared to bring down pollution trapped aloft, by a free air inversion on some occasions. A reduction in fog occurrence however appeared to have one adverse side effect. The increased transparency of the atmosphere rendered photochemical pollution more likely and indirect evidence of perhaps the first such occurrence in the West of Scotland was presented. Increased summer pollution levels were however also on rare occasions attributable to long distance transport from beyond the study area although the trend towards elevated sources and larger power stations may make this phenomenon more common in future.

Finally, the various theoretical conclusions reached were applied to a practical situation, that of Inverkip Power Station, a major new source on the Clyde Estuary. In several respects it was concluded that important omissions and deficiencies in the preliminary analysis of environmental impact were apparent and related to insufficient consideration of microclimatic factors and especially of inversions of temperature. Preliminary analysis of recent sulphur dioxide levels at Linwood lent further support to these conclusions. Future investigations of the impact of new sources should consider these findings when planning the stack height, fuel sulphur content or even general location for such installations.

LIST OF FIGURES

LIST OF TABLES AND PLATES

CHAPTER 1

INTRODUCTION

1.1 Man's Impact on the Atmosphere

Resources have historically been classified under the three headings of land, labour, and capital. Yet none of these categories adequately accommodates air, unquestionably man's most vital resource. The reason for this apparent anomaly relates, as Leighton (1971) suggests, to the continuing tradition of free utilisation. Land, labour and capital entail utilisation costs, involve concepts of ownership, and have thus become subject to regulation by man. The last resource of all to be incorporated into this process of regulation is air, and, as such, the philosophy of free use still frequently predominates.

From the economist's viewpoint (Solow, 1971), air pollution is the inevitable result of the waste disposal capacity of the atmosphere being provided free of charge. A by product of this, which makes the problem so intransigent, is that the costs do not accrue to the party causing them but rather to others utilising the resource. Furthermore, the pollution burden is not confined to air, or water, or land, but is largely interchangeable between these media, emphasising that no one disposal medium can be viewed in isolation. There is thus considerable truth in the contention that there is not an air pollution, or water pollution or solid waste problem as such, but rather a materials disposal problem of which air pollution is but one symptom, however serious.

If, therefore, while the technology to control air pollution undoubtedly exists, economic considerations militate against control, then effective management of the resource concerned is the only practical, though sub optimal, solution. For air pollution in particular, the major control variable is the atmosphere itself and it is with this aim of improved air quality management that this study is concerned.

1.2 The Background to the Air Pollution Project

Towards the end of the 'sixties' an air of optimism regarding the economic future of Central Scotland prevailed. A steady growth in employment was noticeable, despite the continuing decline of several major industries the effects of which were felt most acutely in the Clydeside conurbation. In terms of unemployment, the differential between national and Scottish rates was narrowing from the persistent two to one ratio maintained for so much of the decade, partly in response to a fairly vigorous regional development policy. Incorporating tax, investment, and employment subsidies, such inducements proved particularly attractive to foreign firms anticipating United Kingdom entry into the European Economic Community. With their new technology, their scope for expansion and the opportunities of diversifying employment which they offered, such firms seemed for a while capable of transforming the industrial geography of Scotland.

While the specific choice of Scotland was often conditioned by financial incentives, the attractions of expansion in Britain, particularly for American based multi national companies, were more basic. Possessing the technology and the products which, with relatively minor modifications, could be sold in a European market less competitive than the domestic U.S. market, a location in Britain was also an ideal springboard for further penetration of the growing market in Continental Europe as the companies gained the experience and expertise necessary. Thus in the decade after 1964 a doubling of the number of North American firms in Scotland occurred, accounting for 14.9% of the country's manufacturing employment. In areas such as Tayside and Clydeside this proportion was even higher (Hood and Young, 1977).

It was natural to expect that this success in the light engineering and electronics sectors could be repeated in the heavier sectors, especially oil refining and petrochemicals, and in this context attention naturally focused on the deep water facilities of the Clyde Estuary. Whereas transport and transhipment costs are of relatively minor importance for the light industrial sectors, often labelled 'footloose', such installations as steelworks, power stations, oil refineries and petrochemical plants have specific site requirements in terms of area, water, power, port facilities and communications which render them economic only in certain locations. One such location was the Clyde Estuary where the juxtaposition of flat land, deep water and proximity to a large urban market was particularly favourable. The overall development strategy designed to exploit these immense natural advantages was probably best articulated by the Scottish Council (1970 and 1971) which envisaged the area between the Clyde and Forth Estuaries as a great transhipment zone between large international trade flows and smaller inter European ones, a land bridge between Europe and the rest of the world.

The first of a series of setbacks to this strategy occurred while it was still being formulated. In 1969 the Secretary of State, after a Public Enquiry, refused planning permission to Murco Petroleum for an oil refinery at Longhaugh, principally on the grounds of increased air pollution. Apart from the obvious employment and 'spin-off' benefits of such a development it was especially significant to Renfrew County Council in view of their considerable infrastructural investments at Erskine New Community, Linwood, and in the new high level bridge across the Estuary at Erskine.

The County Council's case at the Public Enquiry had been hindered considerably by a lack of data on atmospheric pollution levels in the area. The dearth of monitoring sites on the estuary can be seen in Fig. 1.1 which shows only two sites continuously operative since the sixties from Glasgow to Irvine. Even these two are located within 2 kilometres of each other in similar built up surroundings. Not surprisingly then, little was known concerning the interaction of relief and climatic factors in influencing the dispersal of pollutants in the area. One of the consultants retained by the Clyde

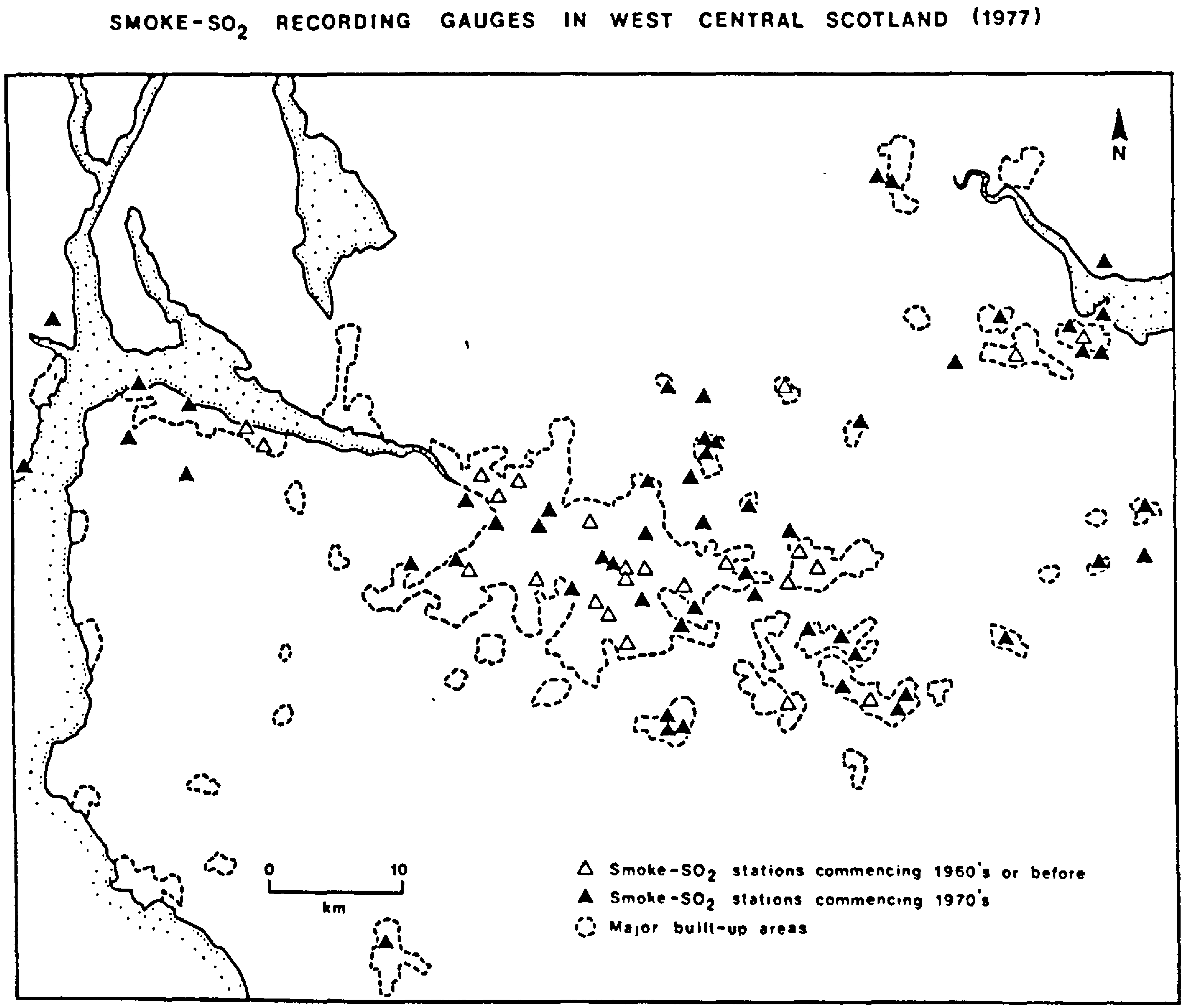


Fig. 1.1 Smoke and Sulphur Dioxide Recording Gauges in West Central Scotland (1977)

Estuary Development Group, Professor Arnold Weddle, expressed this problem in his report (Weddle, 1969):

> 'Investigations have shown how difficult it is to produce concrete evidence as to the production and behaviour of pollutants from future industry. This is because the behaviour of smoke plumes and air currents taking away pollutants is affected by local topography and because a detailed knowledge of micro climate is required, which is not often available.'

It is to be hoped that this study helps remedy some of these deficiencies, even if the scale is rather wider than Professor Weddle might have envisaged.

Other projects remained at the planning stage after the Longhaugh Enquiry for which environmental impact analysis was necessary, particularly with respect to air pollution effects. These included: Bishopton and Ardmore (oil and petrochemicals), Inverkip, Argowan, Irvine and Dundonald (power stations), Inkerman (brickworks), Hunterston (steelworks) and Lochwinnoch (residential development). This encouraged the then Renfrew County Council to participate more fully in the National Survey of Air Pollution supervised by the Warren Spring Laboratory of the Department of Trade and Industry.

The National Survey came into being in 1959 partly as a means of implementing and monitoring the 1956 Clean Air Act. Prior to this, systematic measurements of air pollution had been undertaken voluntarily by the Committee for Investigation of Atmospheric Pollution which was formed in 1914. Fifty years later daily concentrations of smoke were measured at 193 sites, sulphur dioxide at 140, monthly grit and dust fall out at 993 sites and monthly sulphur dioxide using a standard lead dioxide candle at 1,115 sites. (Warren Spring Laboratory, 1972). The principal emphasis lay in environmental improvement based on smoke control, an emphasis which the Clean Air Acts continued. A legacy of this is apparent today in the disproportionately low percentage of the National Survey's 1,279 sites (1976) which are located in rural areas, only some 12½%. The bulk of these rural stations are maintained by the Central Electricity Generating Board as monitors on new and projected power stations. However, the difficulties to which such a biased distribution lead are only too obvious as the particular case of Longhaugh demonstrated. The location of large new sources of SO_2 on the coast or generally in non residential areas now means that rural - urban contrasts are becoming blurred. According to the National Society for Clean Air (1971) different parts of the country, whether urban or rural appear to be moving towards a roughly similar concentration level. The focus is shifting therefore slightly away from the urban areas to the rural - urban fringes where increased concentrations are often in evidence or where certainly any decline is less marked. This is also clear from Fig. 1.1. Even fairly remote rural locations are assuming greater importance due to recent evidence that under certain conditions the fumigation of effluent transported considerable distances may occur. (Garnett, 1976).

It was on such a rural - urban fringe that Renfrew County Council established their small network of three monitoring stations which began reporting to the National Survey between June 1971 and June 1973. During this period several other monitors were established, especially in East Kilbride and in the vicinity of Inverkip, considerably augmenting the sparse network existing during the sixties. The data produced from the three sites at Linwood, Erskine, and Lochwinnoch have been analysed in conjunction with meteorological data obtained nearby and elsewhere and use has already been made of it for planning purposes and in academic research. (Halstead, 1973).

1.3 The Study Area - West Central Scotland

One of the keys to understanding the controls on pollutant dispersal in any region is the particular relief of the area. This introduces the problem of uniqueness, familiar to geographers, which has rendered so many individual studies of only limited applicability outside their particular area. (Elsom, 1976, Bringfelt, 1971, Smith and Jeffrey, 1971). This means that the derivation of results in one area with relevance in another area is rare since the inter-relationship between the emission pattern and the relief influences on its dispersal are so complex. Weddle (1969), articulated this with respect to West Central Scotland:

> 'The (air pollution) problem is most severe in the River Clyde Valley due to the combination of topography, micro climate, and the location of existing sources of pollutants. Air flow is channelled through the valley by the surrounding mountains, especially when the prevailing West and South-West winds are blowing. The valley shape also encourages the frequent development of temperature inversions ; under such conditions pollutants are trapped and become concentrated'.

The complexity of relief and meteorological influences on dispersal is apparent, rendering the possibility of constructing a predictive model, with application elsewhere, unlikely except in very general terms. Further evidence on the interaction of relief on dispersal can be seen in later sections concerned with inversions of temperature. However, in order to establish a framework for further analyses it is useful at this point to examine the more general physical characteristics of the study area.

Physical or administrative boundary lines on a map are seldom recognised by atmospheric processes. It is neither practical nor desirable, therefore, to delimit a 'study area' for which all data is tailored. But while not defining 'senso stricto' such an area it is organisationally helpful to indicate a broad core and periphery relevant to this study. Fig. 1.2 shows the focus of attention on the area between Glasgow and the Clyde Estuary with a peripheral zone extending from the edges of the

MAIN URBAN AREAS, ALTITUDE AND RELIEF

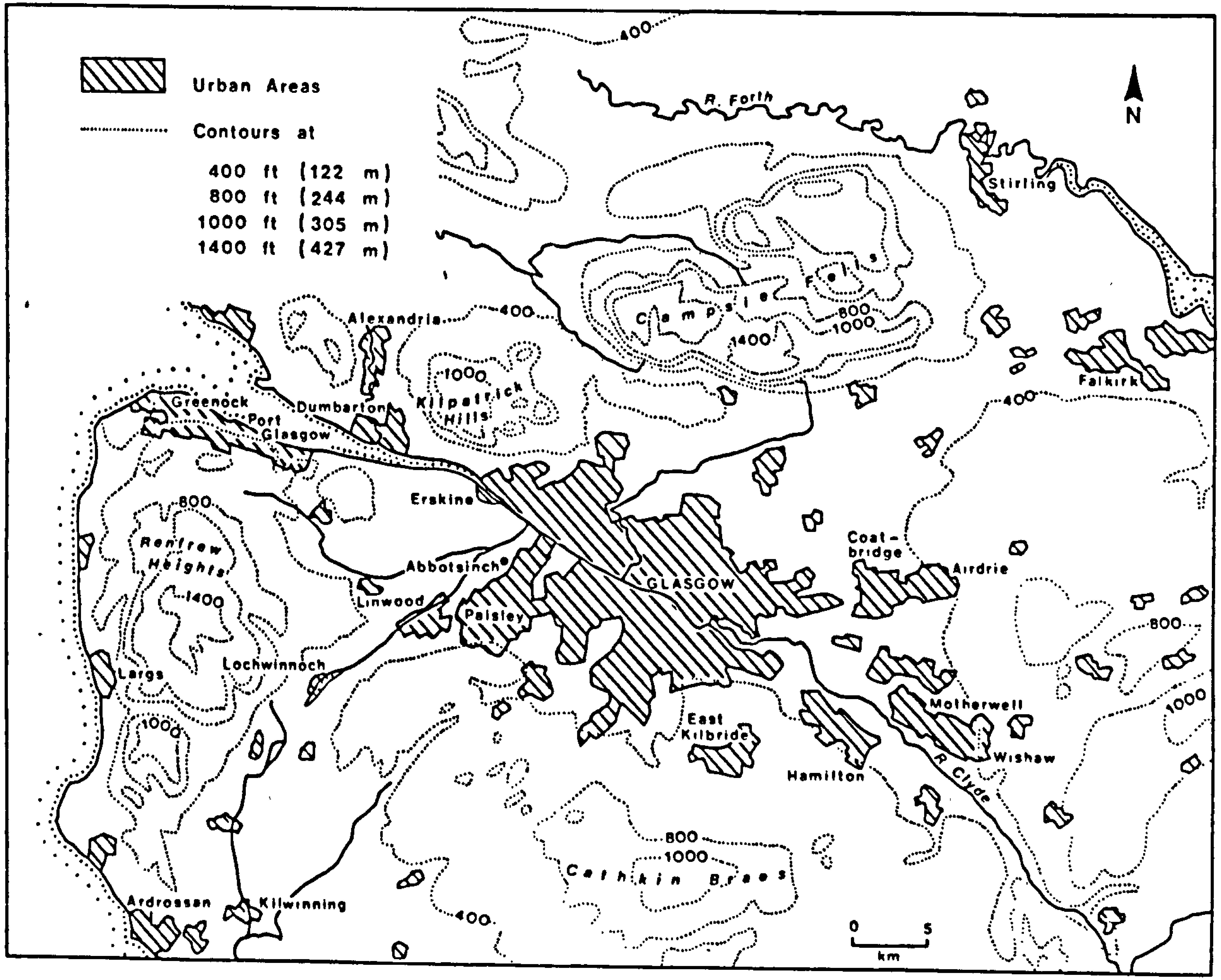


Fig. 1.2 Main Urban Area, Altitude and Relief

Highlands and Southern Uplands to the Forth Estuary in the east. It is at once apparent that a considerable diversity in relief exists. Comprising about 4,000 square kilometres, about half the area is below 100 metres O.D., largely accounted for by the 'Howe' of the Glasgow Basin. This in turn is dissected by the Clyde and its tributaries crossing the area from south east to north west. At its widest point, in the vicinity of Glasgow, the drainage basin extends north eastwards through the Cumbernauld Gap via the Kelvin Valley, and south westwards through the Lochwinnoch Gap via the Black Cart Valley. Around this basin, arranged so as almost completely to enclose it, are a series of bleak plateaux, composed of Carboniferous lavas, stretching from the Campsie Fells in the north through the Kilpatrick Hills and Renfrew Heights to the Cathkin Braes in the south. To the east Carboniferous sandstones, limestone and coal measures rise to over 300 metres O.D., although more gradually than their western counterparts.

The modal values occurring in the height range 200-400 metres on the hypsogram (Fig. 1.3) largely reflect the occurrence of these high moorlands. Rising to 600 metres, they are highly significant influences on the pollution climatology of the Central Scotland area. Their prime effect, of enclosing the drainage basin, was pointed out by Miller (1958). Fig. 1.4 shows how, below 100 metres O.D., only three small gaps exist which remain distinct even up to 300 metres O.D. If reference is made to the directional wind rose for Abbotsinch Airport (Fig. 7.1) it will be appreciated that such a relief configuration exerts a noticeable influence on air movement, and with it airborne pollution, deflecting and channelling it along certain preferred trajectories which figure slightly more prominently in the wind rose than might otherwise be expected. In addition, however, it will be later shown that the surrounding high tablelands mentioned act on occasion as cold air reservoirs providing surges of cold air which drain into

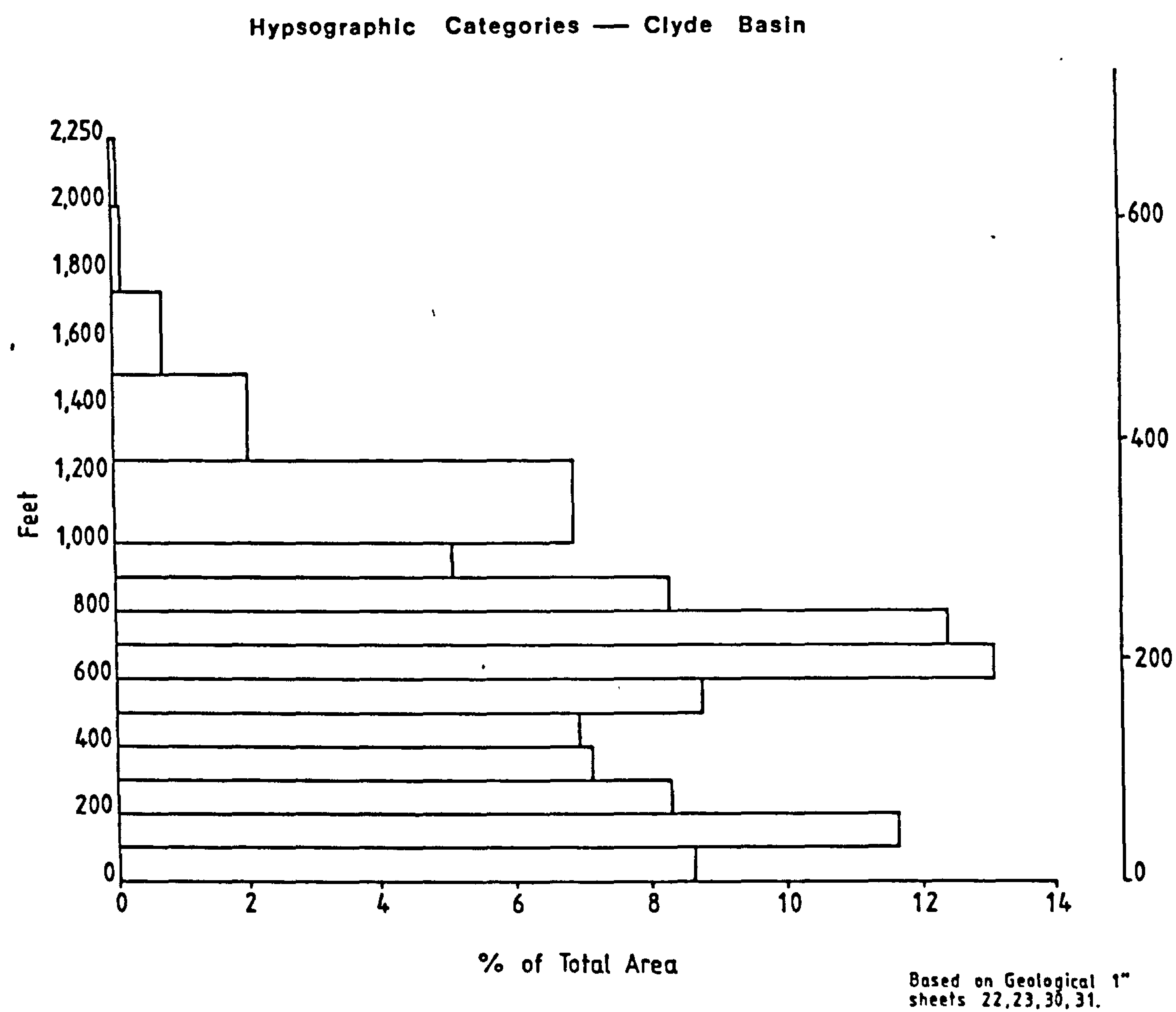
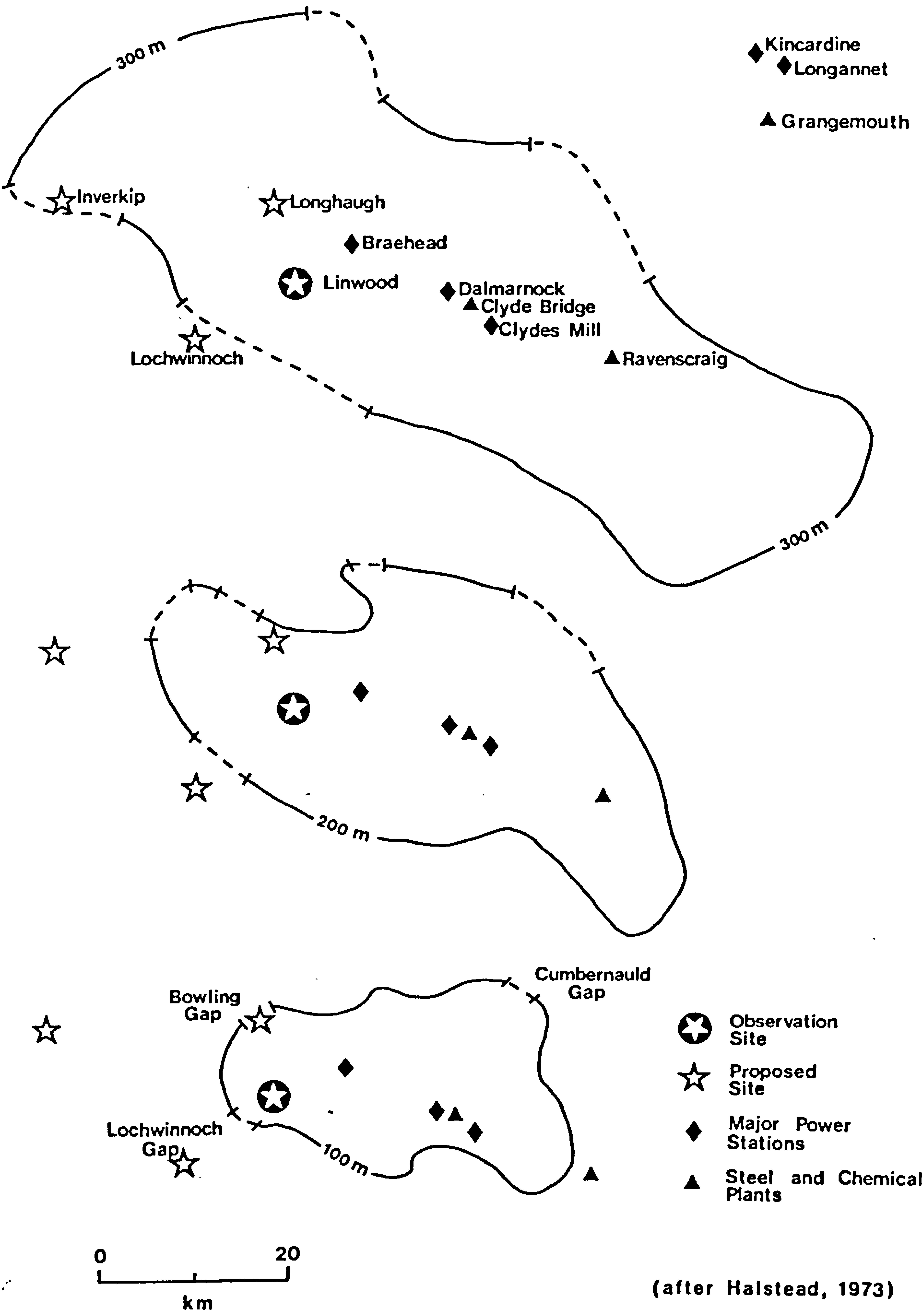


Fig. 1.3 Hypsographic Categories - Clyde Basin

GENERALISED CONTOURS - CLYDE BASIN



(after Halstead, 1973)

Fig. 1.4 Generalised Contours - Clyde Basin the basin on calm, cloudless nights. As well as increasing fog and frost frequency such a mechanism establishes a shallow ground based inversion of temperature in the layers of air near the ground which may trap low level emissions giving rise to increased pollution concentrations.

Beyond these lava plateaux lie the faulted massifs of the Highlands and Southern Uplands, exerting an influence at a higher level. Summit heights commonly range just below 1000 metres O.D., about 200 metres less in the Southern Uplands. The exposure of the central rift valley to the prevailing south west winds is apparent, explaining the generally good pollutant dispersal capabilities of the area. On occasion, however, this dispersal mechanism falters. Relief influences are generally apparent on such occasions which give rise to the periods of enhanced ground level concentrations of smoke and sulphur dioxide which this study is concerned with.

CHAPTER 2

THE BACKGROUND TO THE AIR POLLUTION PROBLEM

2.1 Nature and Occurrence

The continuous acceleration in the rate of technological change over the last few decades has forced man to reconsider two of the foundations on which his headlong rush for industrialisation has been founded. The first of these involves an implicit assumption that the benefits of exploiting to the full the earth's natural resources will always exceed any diseconomies produced as a side-effect. Secondly, although closely related, it is assumed that any such side-effects will, being of such insignificance relative to natural processes, not upset the functioning of the natural system. The ignorance which such assumptions involves is only gradually becoming apparent as the significance of the interaction between man and nature is being more fully appreciated.

One such strand of enquiry has centred on the as yet unknown impact of anthropogenically derived heat and airborne waste on the delicately balanced global atmospheric system. Workers such as Sellers (1969) and Budyko (1970) claim that a decrease in the solar constant of as little as 1.6% could initiate widespread glaciation. It is, however, equally conceivable that increased turbidity due to atmospheric pollution could achieve the same result, such is the responsiveness of the atmospheric system, to any externally induced change in the status quo. Yet, in this field also, the complexity of the processes involved is such that no agreement exists and diametrically opposed views continue to circulate. Contrast the three following opinions which appeared in the same scientific periodical within a space of only a few months.

> '....the net effect of the manmade particulates seem to be that they lead to heating of the atmospheric layer in which they abound. This is usually the stratum hugging the ground. All evidence points to temperature rises in this layer, the opposite of the popular interpretations of the dust effect.'
>
> (Landsberg, 1970)

> '....the present urban aerosol-surface albedo environment would produce a warming trend of solar radiation were it the only thermal process acting. On the other hand, the aerosol-albedo combination characteristic of the desert environment and prairie environment appears to produce cooling trends.'
>
> (Attwater, 1970)

> '....If this increased rate of injection of particulate matter in the atmosphere should raise the present global background opacity by a factor of 4, our calculations suggest a decrease in global temperature by as much as 3.5^{o}K. Such a large decrease in the average surface temperature of Earth, sustained over a period of a few years is believed to be sufficient to trigger an ice age.'
>
> (Rasool and Schneider, 1971)

On a less dramatic scale global changes in temperature are believed by Smagorinsky (1963) to influence the latitudinal location of the sub tropical anticyclones, with particularly significant effects on precipitation levels in sahelian zones. This viewpoint has been restated by Bryson (1973) who diverts the argument away from whether or not particulates and gaseous pollutants are warming or cooling the atmosphere to the more immediate one of whether or not their effect is to suppress monsoon activity and the life giving rain associated with it.

Table 2.1 shows the normal constituents of dry, clean air near sea level. The dominance of nitrogen, oxygen and to a lesser extent Argon is noted, accounting for about 99.96% by volume of such a sample. The remainder is accounted for by carbon dioxide, helium, neon and methane with only traces of carbon monoxide, ozone, nitrogen dioxide and sulphur dioxide. These trace values, however,

Table 2.1 Composition of clean, dry air near sea level

Component	Concentration (p.p.m.)
Nitrogen	780,900
Oxygen	209,400
Argon	9,300
Carbon dioxide	318
Neon	18
Helium	5.2
Methane	1.5
Hydrogen	0.5
Carbon monoxide	0.1
Ozone	0.02
Nitrogen dioxide	0.001
Sulphur dioxide	0.0002

Source: Report, American Chemical Society 1969.

are considerably enhanced in polluted air, often by a factor of several hundred. (Table 2.2). The greatest increase obviously occurs with sulphur dioxide which, together with particulates, is therefore the major index of air pollution used throughout the world. In the United Kingdom about 6 million tonnes per annum are emitted, more than the smoke and all other gaseous pollutants (not counting carbon dioxide) combined. Of lesser importance are the oxides of nitrogen (Table 2.3) over half of which come from petroleum sources and which are so instrumental in reactions with oxidant gases in producing the photochemical smog so characteristic of California and similar climatic areas. Such photochemical reactions have recently been identified over London (Ball, 1976) and later in this study what is probably the first such significant photochemical pollution episode in Scotland is examined.

The main pollution indicators are still smoke and sulphur dioxide, however, two pollutants which normally occur together and which act synergistically. This renders the definition of limits or standards difficult, since the effect of one or other pollutant acting on its own is difficult to assess in isolation. Both, however, have played distinctive roles when considered in a historical dimension in the United Kingdom. Smoke to some extent epitomises the early industrial age when coal was the major source of energy, while SO_2 is today principally produced from oil combustion, a process which has characterised the post war growth of manufacturing industry throughout the world.

Table 2.2 Composition of a typical polluted city atmosphere (Chicago)

Pollutant	'Natural Level' p.p.m.	Mean Annual p.p.m.	Max. Daily p.p.m.	% enhancement	Max. hourly p.p.m.	% enhancement
Sulphur Dioxide	0.0002	0.135	0.790	395,000	1.36	680,000
Nitrogen Dioxide	0.001	0.042	0.130	13,000	0.22	22,000
Total Oxidant	0.02	0.004	0.070	350	0.22	1,100
Total Hydro-carbon	—	3.2	6	—	12	—
Carbon Monoxide	0.1	7.6	19	19,000	36	36,000

Source : Lynn, D.A. and McMullen, T.B., (1966).

Table 2.3 Estimated Emissions of Nitrogen Oxides in the United Kingdom during 1970

Source	NO_x (10^3 tonnes)
Transport	
Petrol Engines	203
Diesel Engines	62
Railways	5
Domestic Sources	
Coal Fires	39
Smokeless Fuel Fires	10
Gas Appliances	15
Oil-fired Central Heating	4
Commercial Sources	
Fuel and Gas oil Central Heating	53
Coal and Coke	156
Gas	14
Industrial use of Fuel and Gas Oil	299
Incinerators	2
Power Stations	
Oil-fired	86
Coal-fired	514
Total Emissions	1,462

Source : Derwent, R.G. and Stewart, H.N.M., (1973).

2.2 Smoke and Smoke Control

Solid and liquid particulate pollution has largely come to be synonymous with smoke, in the United Kingdom at least. Almost invariably both descriptions relate to the same problem, that of coal combustion. Strictly speaking, however, the term 'smoke' should only be used to describe the fine carbonaceous particles and minute tar droplets resulting from incomplete fuel combustion. Classification on the basis of diameter size is possible:

$$0.0002\mu m < \text{fume} < 1\mu m < \text{dust} < 76\mu m < \text{grit} < 500\mu m$$

(Clean Air Regulations, 1971)

Measurement of smoke concentrations is normally made using the same sample of air utilised for the determination of sulphur dioxide content. Particulate matter is removed by passing the air sample through a filter paper prior to it being drawn through the hydrogen peroxide solution. The stain left on the filter paper is examined with a reflectometer which determines the degree of opacity. This quantity in turn is related to calibration tables which enable determination of the particulate concentration according to the following formula:

$$C = \frac{F}{V}\,(91,679.22-3,332.0460R+49,618884R^2 -- 0.35329778R^3+0.0009863435R^4)$$

where

C= Concentration in microgrammes per cubic metre

V= Volume of sample in cubic feet

F= 0.288 for ½ inch clamp

1.000 for 1 inch clamp

In addition to solid material the standard filter paper also obstructs the passage of aerosols, often consisting of tar droplets below 100µm diameter.

The problem of smoke pollution is not one of Victorian Britain only. For many centuries it has been an unwanted by product of the early industrialisation of Britain relative to the rest of the world. Even as early as the 17th Century John Evelyn (1661) could write:

> '....what is all this but that Hellish and dismall Cloud of Seacoale?......the City of London resembles the face rather of Mount Etna, the Court of Vulcan, Stromboli, or the Suburbs of Hell, than An Assembly of rational Creatures.......'
>
> (Evelyn, 1661)

Yet however poetically Evelyn, or even Dickens (1853) could express their feelings on smoke, and however attractive the yellowed urban skies of Monet or Pissaro might look, levels of smoke pollution gave rise to real concern. In 1909 the West of Scotland learned of the problems during a major episode when atmospheric dispersion processes failed. Under similarly stagnant meteorological conditions in 1952 in London 4,000 excess deaths occurred, leading directly to the passage in 1956 of the Clean Air Act. This law prohibited, for those factories to which it applied, the production of black smoke. Exemptions from the requirements of the Act, as with the Alkali Act of 1906, were granted to factories concerned with military production.

Smoke emissions dropped rapidly in the few years following 1956, declining from 2.5M tonnes in 1950 to below 0.5M tonnes in 1978. Most of the improvement is attributable to the reduction in industrial emissions which are at present only a fraction of their former total of 1M tonnes (Fig. 2.1). Domestic emissions account for the largest part of present day emissions. However, it should be realised that this reduction in smoke emissions occurred at a special time in the British post war economic cycle. The 1950's and 1960's were the decades of the consumer boom, when rapidly growing world trade and a reaction against wartime austerity combined to produce a period when consumption, particularly of domestic durable goods like washing machines, televisions, cars etc.

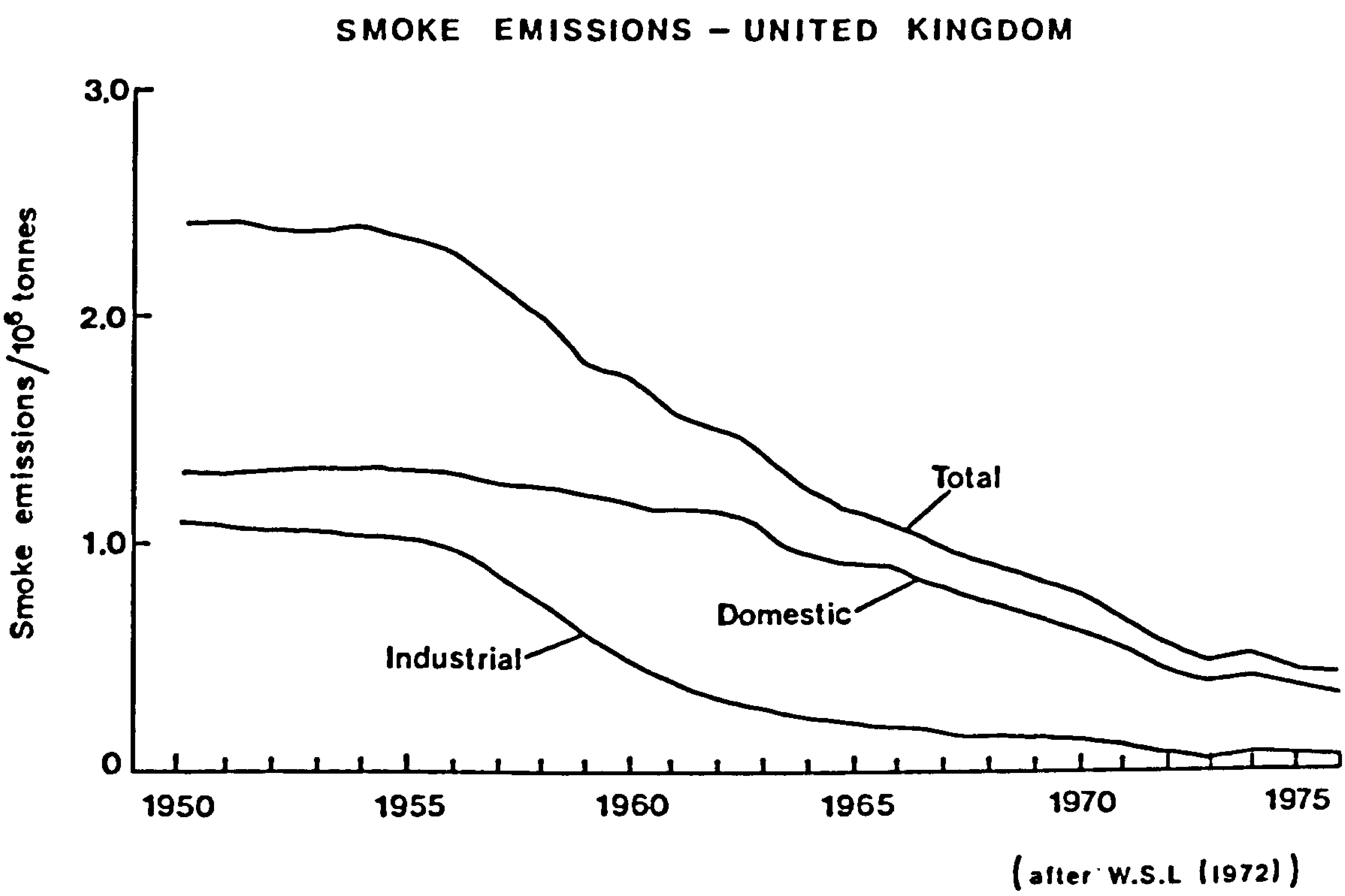


Fig. 2.1 Smoke Emissions - United Kingdom

rose to unprecedented levels. Light engineering and electronics based industries, geared to supply this market, grew rapidly, requiring as their energy source electrical power from the expanding National Grid rather than coal availability. Smoke emissions thus have declined as the demand from industry for electricity has risen. Following on from this, an inverse relationship is apparent between the level of smoke emissions and the level of oil imports, prior to the advent of North Sea gas and oil. The ultimate exhaustion of these resources in the not too distant future, however, means that coal combustion will remain a significant, perhaps even growing, component in United Kingdom energy supplies. From this viewpoint it would be wrong to consign smoke emissions into an insignificant category in forward planning of industrial environments.

Ground level smoke concentrations, unlike their SO_2 counterparts, have mirrored the decline in emissions, at least in urban areas. (Fig. 2.2). In this respect the Clean Air Acts have achieved what they set out to do. However, it would be naive to claim that the Clean Air Act was, or is, the perfect instrument for curtailing urban smoke levels. One basic criticism appears to be the application of emission standards which are not geared to ambient air standards. In applying the Act, also, a rather clandestine approach is apparent with individual negotiations at factory level occurring between firm and inspector. 'Gentlemen's agreements' abound which may relate to the firms economic ability to satisfy abatement requirements rather than a strict interpretation of the Act. (Rees, 1977). Supervision of arrangements is inevitably slack due to the relatively small number of inspectors employed, only 35 in 1972. It is therefore not surprising that only 2 prosecutions under the Alkali Acts were made between 1920 and 1966.

Variations at plant level are compounded at the regional scale by massive discrepancies in terms of smokeless zoning policy. Areas like South Wales have a historical tradition of hostility to smokeless zones which shows in Table 2.4 while in the newer residential areas of the

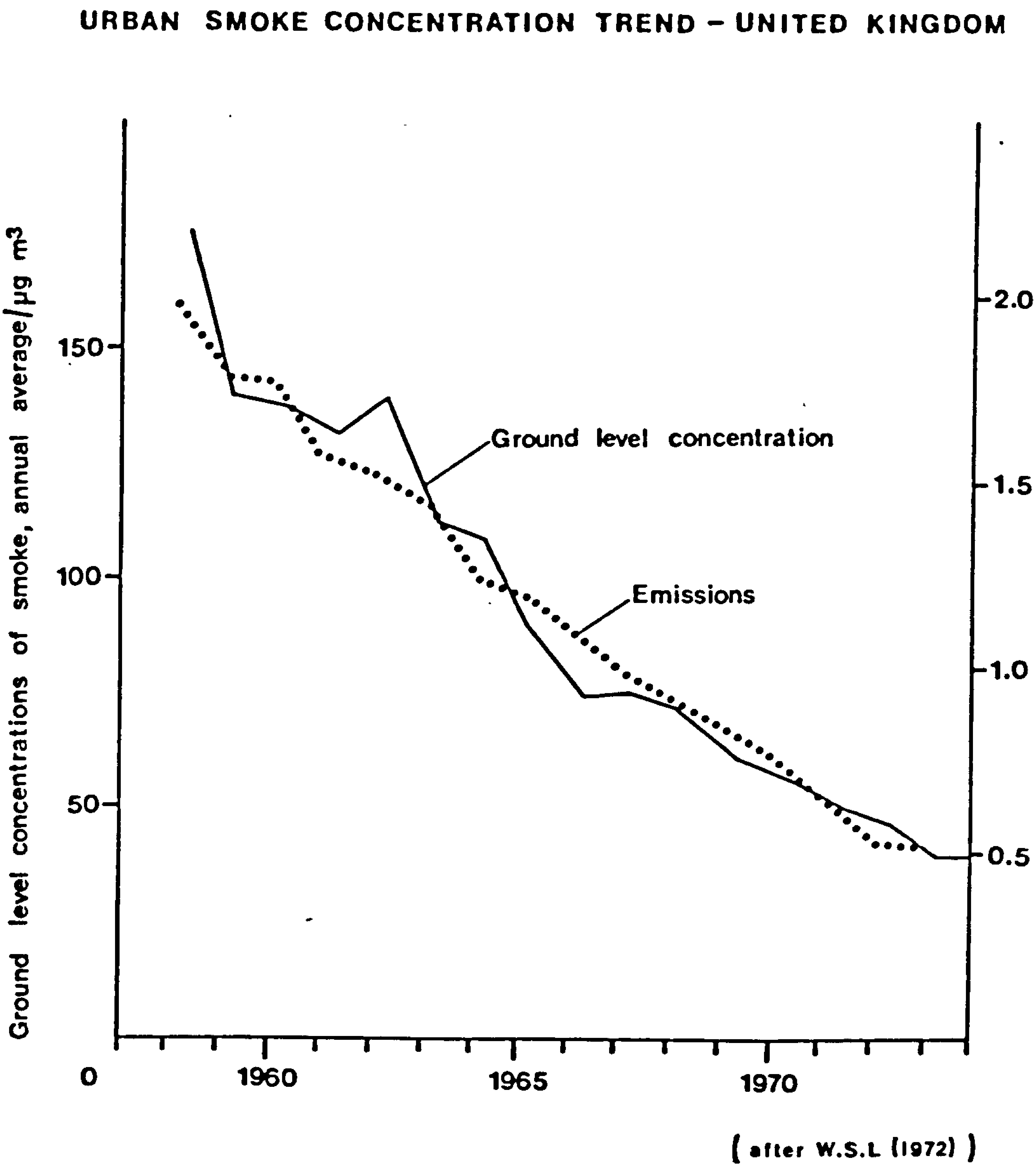


Fig. 2.2 Urban Smoke Concentration Trend - United Kingdom

Table 2.4 Regional Variations in the Adoption of Smoke Control Zones in 1970

Region	Percentage of "black areas" covered by smoke-control zones.
Northern	31.9
Yorkshire and Humberside	49.6
East Midlands	24.3
West Midlands	34.4
Greater London	73.8
North West	49.2
South West	28.5
Wales	0.01

Source : Rees, J, (1977).

country, like South East England, away from the coalfields, progress is more rapid. Traditional coal burning areas have been slow to switch to other fuels, perhaps fearing a further contraction in a coal market in long term decline. South Wales in particular always maintained that smoke was not a problem, and a glance at Fig. 2.3 would seem to confirm this. This introduces a further criticism of the Act in that it seems difficult to assess the need for smokeless zones where only smoke is controlled and other, often more harmful pollutants are permitted. In urban areas, in particular, increased emissions from automobile exhausts have largely taken over smoke's former niche.

The question arises as to whether conditions would be worse or not today in the absence of the Clean Air Act. If smoke concentrations at Kew from 1922 are plotted the trend line, before and after the Clean Air Act, is unchanged. This would seem to suggest that the Clean Air Regulations have made no impact and a similar reduction in smoke concentrations would have occurred in their absence. Of course Kew may not be representative of national trends, and, as will be seen later, even more marked reductions in smoke values seem to have occurred in Central Scotland. But nevertheless, the evidence at Kew indicates that an extrapolation of trends existing before 1956 would have produced similar concentration levels today. (Fig. 2.4). It should, however, be pointed out that the mere continuance of the trend over this period is a worthwhile achievement. Lamb (1972) confirms that a considerable slackening in the vigour of the westerlies in the hemispheric circulation was occurring during this period, (Fig. 2.5). A corollary of this is that an increased incidence of blocking anticyclones must have been observed. It will be shown in Chapter 8 that the subsidence inversion associated with such high pressure cells is instrumental in producing conditions leading to the trapping and enhancement of pollution. In this respect, therefore, the maintenance of a declining trend

WINTER MEAN CONCENTRATION OF SMOKE, 1975 - 6

Fig. 2.3 Winter Mean Smoke Concentration 1975-6 - England and Wales

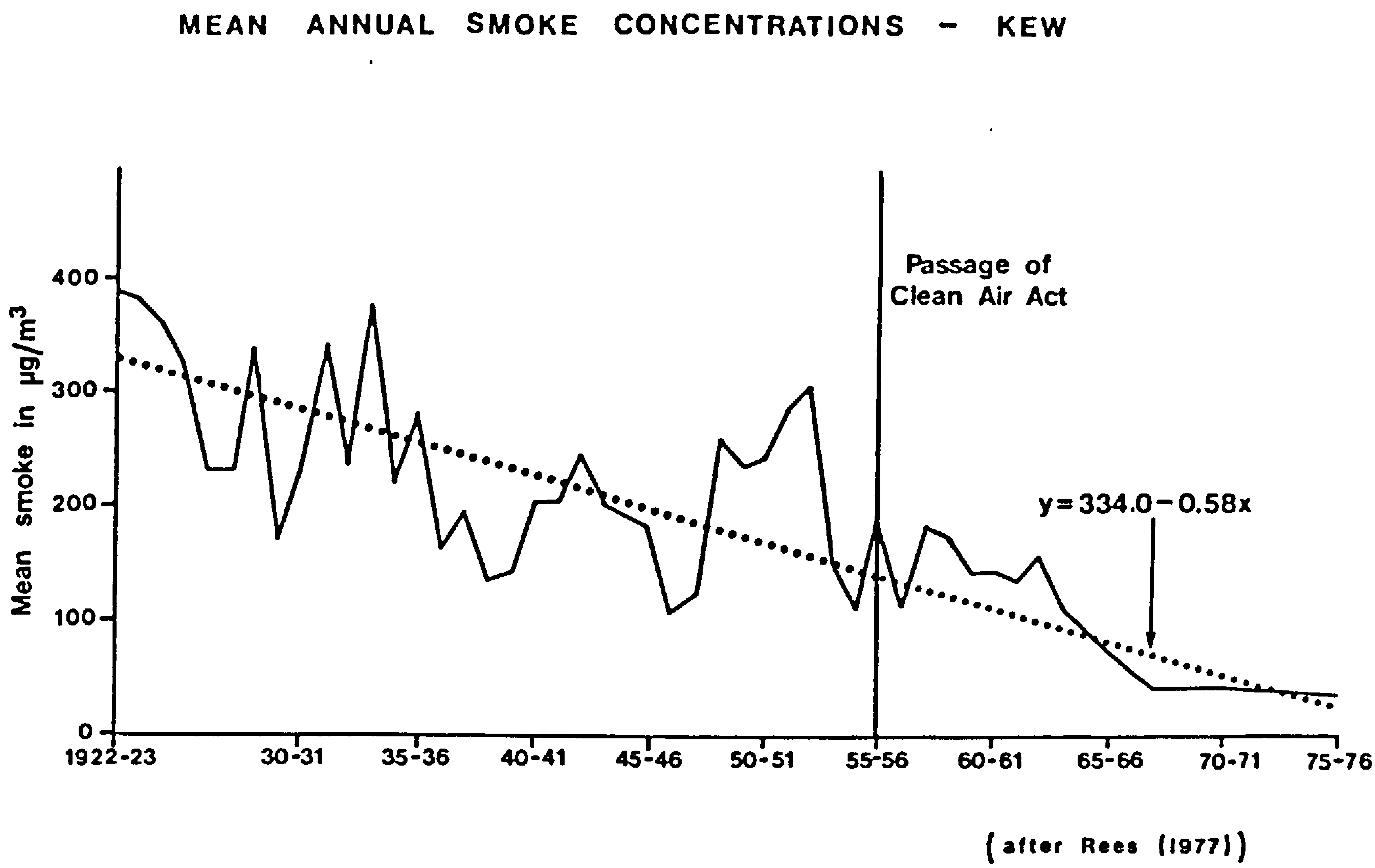
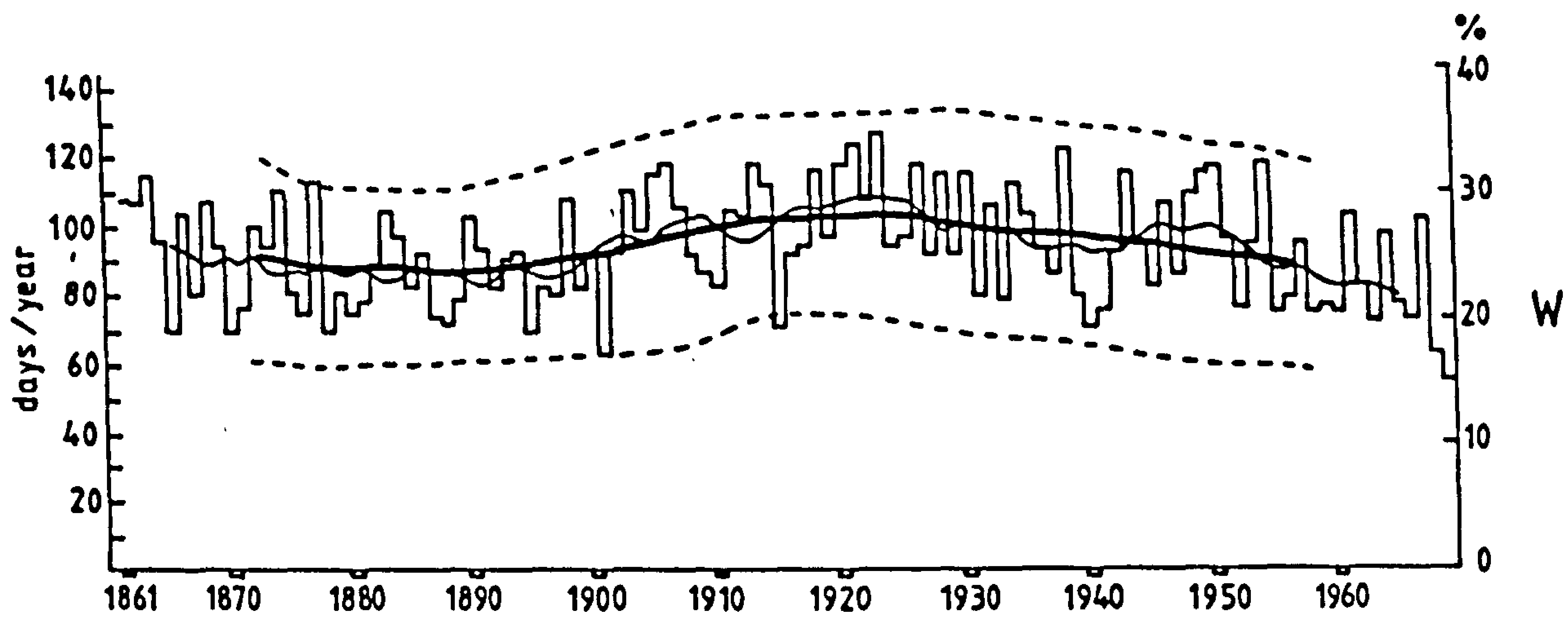


Fig. 2.4 Mean Annual Smoke Concentrations - Kew

Frequency of the westerly type over the British Isles



Yearly frequency — 10-year averages — 25-year averages

---- Departure from the 25-year mean amounting to twice the standard deviation

An allowance is made for the appropriate share of hybrids involving Southerly, Anticyclonic or Cyclonic.

(after Lamb (1972))

Fig. 2.5 Frequency of the Westerly Type over the British Isles in smoke concentrations during this meteorologically unhelpful period must be viewed as a considerable achievement.

As might be expected, particulate matter shows a tendency to settle out of atmospheric suspension under the effect of gravity. This is confirmed by the strong correlations between ground level concentrations and nearby low level sources (Marsh and Foster), 1967). The heaviest particles settle out first while those of diameter around 5µm take much longer, perhaps impacting on a surface or another particle. Rain is a particularly efficient scavenger and Greenfield (1957) has estimated that a rate of rainfall of 1mm/hour sustained for only 15 minutes removes about 28% of medium sized particles from the volume of air through which it passed. Equally so, the presence of minute particles suspended in the atmosphere provides potential condensation nuclei which tend slightly to increase precipitation amounts in polluted areas and in adjacent areas downwind of them. The phenomenon has been widely documented (Bach, 1972) ranging from the reputed increase in hail frequency in La Porte, Indiana to increased precipitation during weekdays in Paris.

Particulate emissions originate from a variety of sources. A breakdown of these for industrial sources in the United States can be seen in Table 2.5. Comparable data is not available for the United Kingdom although it seems reasonable to assume that the breakdown would be roughly similar, though perhaps stone crushing would be less significant. In any case considerable advances in the field of dust extraction before emission are now being made and for the foreseeable future it may resonably be expected that continued, if somewhat less spectacular, progress in the control of particulate pollution is very probable.

Table 2.5 Estimated Emissions of Particulate Materials from Industrial Sources in the U.S.A. during 1968

Source	Quantity Emitted (x 10^3 tonnes)
Fuel Combustion	
Coal - Electricity	2820
Coal - Industry	2350
Oil - Electricity	33
Oil - Industry	95
Natural Gas	98
Stone crushing, sand and gravel	4170
Agriculture	1603
Iron and steel production	1290
Cement production	846
Manufacture of timber products	604
Lime	519
Clay industries	425
Primary non-ferrous metal production	431
Fertilisers and phosphate rock	296
Asphalt paving and roofing	198
Ferrous alloys	145
Iron foundries	130
Secondary non-ferrous metal processing	115
Coal cleaning	85
Manufacture of carbon black	84
Oil refining	41
Manufacture of acids	15
TOTAL EMISSION	16350

Source : Vandegrift, A, et al, (1971)

2.3 Sulphur Dioxide

The story of partial success in the control of smoke emissions is not repeated for the case of sulphur dioxide emissions. Accompanying an estimated 80% reduction of smoke emissions from 1950 to the present day has been a perceptible increase of about 30% in SO_2 emissions, to total today some 6M tonnes for the United Kingdom as a whole. From Fig. 2.6 it is at once apparent that the bulk of this increase is accounted for by the rise in emissions from power stations, which has trebled during the period, and now accounts for half the national total. Such an increase implies a considerable rate of growth in energy demand, a phenomenon common to all advanced industrial countries during the last few decades. Guildberg (1977) has shown an average annual rise of 4.3% in energy demand in the United States in recent years as against a comparable rise of 3.5% in per capita gross national product. These figures, however, relate to a period of cheap oil supplies and in the years to come a much slower growth in energy demand seems inevitable as energy becomes relatively more expensive.

Accompanying this trend in power station emissions has been a steadily falling trend in domestic emissions and a slightly falling trend in industrial emissions. Fuel substitution is obviously at the root of these differences. As consumers turn away from coal for domestic space and water heating in favour of light fuel oil, gas and electricity, a trend of reduction in domestic emissions similar to that of smoke is apparent. Power station emissions are to some extent a mirror image of this trend. The slight levelling off in their upward trend from about 1963 to 1968 is undoubtedly due to the coming into service of the first generation of nuclear power stations, a feature which will probably be repeated in the middle and late 'eighties' as the new generation of P.W.R's and A.G.R's come into service.

Essentially what has occurred with SO_2 emissions has been a switch from low level domestic sources to high

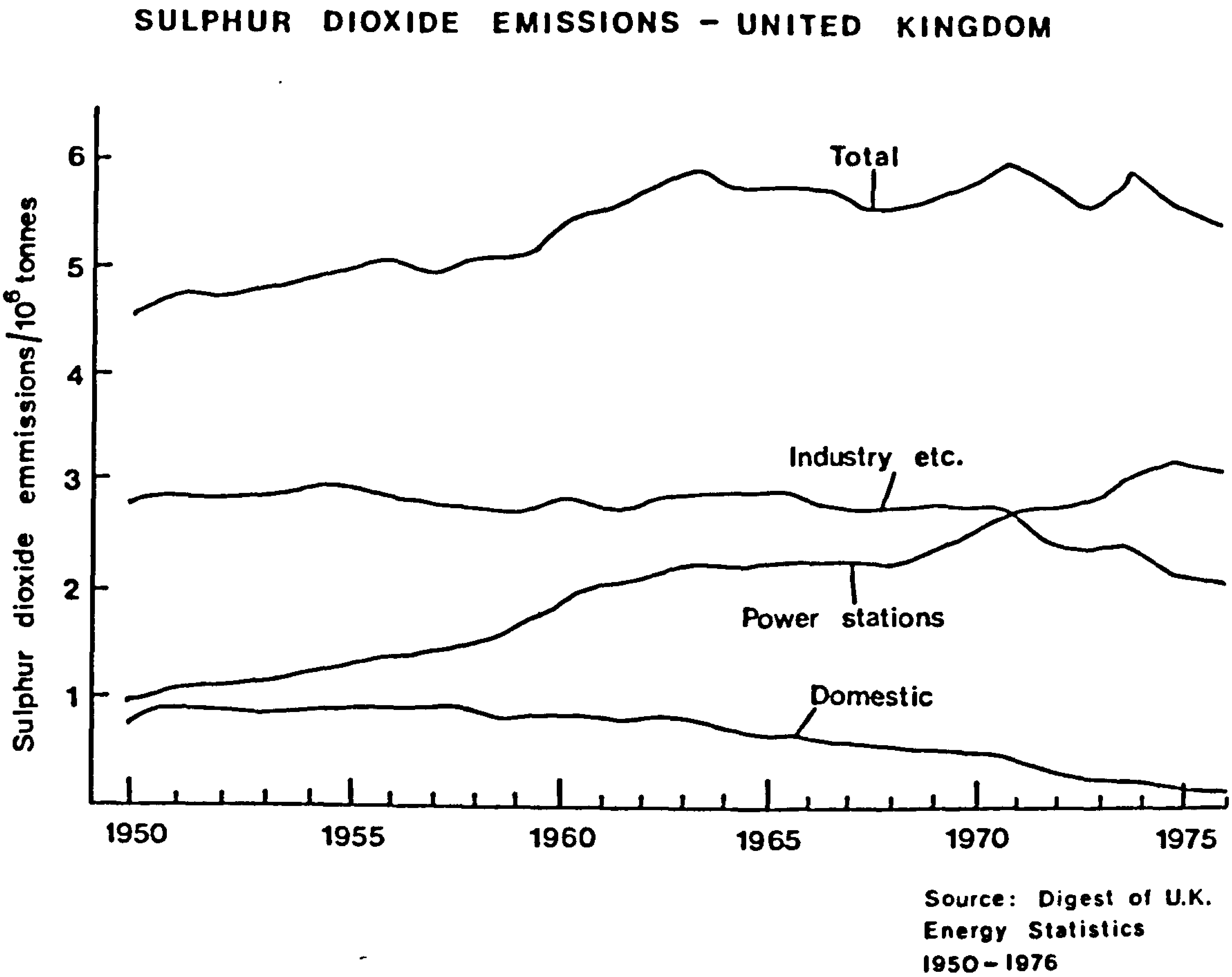


Fig. 2.6 Sulphur Dioxide Emissions - United Kingdom

level power station sources. Accordingly it is not surprising that urban ground level concentrations have fallen markedly during a period of increasing emissions. Reference to Fig. 2.7 illustrates how closely the fall parallels the decline in domestic low level sources. The rate of decrease in concentrations is only slightly lower than that for smoke described above. It must be admitted however, that such figures do distort reality to some extent. Part of the reason for the difference between emissions and urban concentrations relate to the trend, mentioned in Chapter 1, of locating large new industrial installations, particularly power stations, on the coast or in rural locations. Cooling water availability, and the minimisation of fuel supply costs are largely responsible. Much of the increase in emissions, therefore, has taken place from high sources in non urban locations and, being well dispersed by the time it reaches a town or city, contributes little to ground level concentrations. At the same time the development of these large new installations frequently results in the closure of obsolete plant, often in urban locations. This has been observed in West Central Scotland where the provision of large new power stations on the Clyde and Forth Estuaries has been accompanied by the closure of many small power stations such as: Bonnybridge, Clyde's Mill, Kilmarnock, Pinkston, Yoker and Braehead. In such circumstances it is easier to understand the reasons behind a falling trend in urban concentrations and, at least until recently, a rising trend in total emissions.

Dispersal of this high level effluent is not always achieved, as will be seen later, largely due to the effects of high altitude thermal inversions. Under such circumstances control policies based on 'emit hot and high' achieve only a modicum of success, basically shifting the problem downwind. Not only does this have international consequences in terms of damage caused in neighbouring countries (Swedish Royal Ministry for Agriculture and Foreign Affairs, 1971, Holt-Jensen, 1973) but implications on a more local scale are also apparent. Advocates of high stack dispersal policies like Nonhebel (1960) and Lucas (1975) implicitly assume that in projecting local

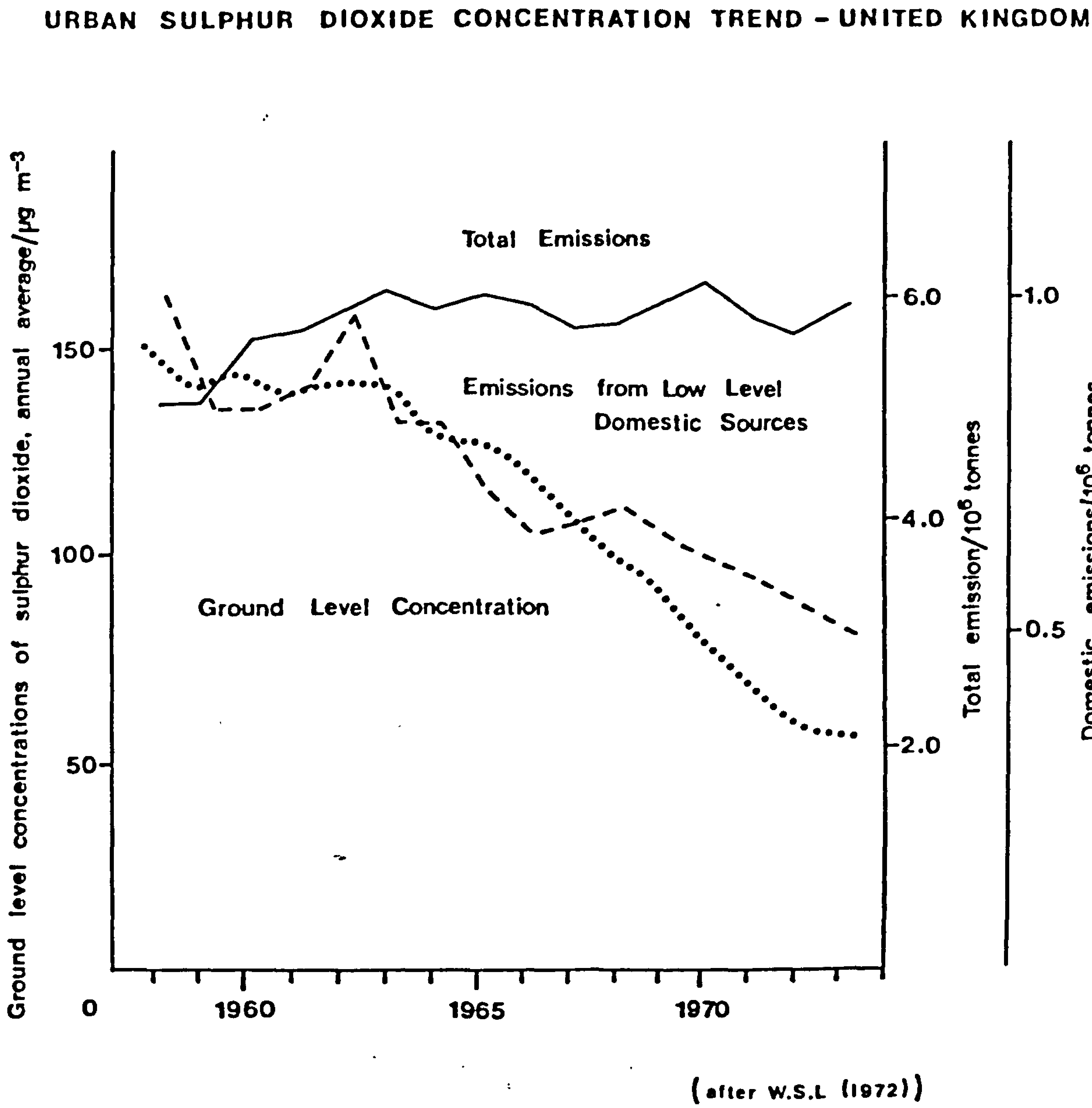


Fig. 2.7 Urban Sulphur Dioxide Concentration Trend - United Kingdom

pollution further afield the beneficial effects on local ground level concentrations are not being counteracted by adjacent areas doing likewise. The problem of long distance transport of SO_2 from high level sources is a growing one and will be discussed in Chapter 14 in relation to West Central Scotland; but certainly clear evidence exists that considerable amounts of sulphur dioxide are imported into the basin from high level sources on the Firth of Forth and beyond. In such a situation of greatly increased pollution exchange between areas the importance of a meteorological approach can be understood.

Sulphur dioxide is readily deposited upon contacting most materials. This arises from the polar nature of its molecules which hold it by attraction on many surfaces, often yielding quite high concentrations in a relatively short time period (Gilbert, 1968). Vegetation thus has a strong cleansing effect on polluted air with which it comes into contact (Gilbert, 1969). Gilbert found unexpectedly low SO_2 concentrations in a wooded area of central Newcastle while O'Hare (1974) found similar 'islands' of clean air in sheltered parks and woodland in the Glasgow area. A measure of protection from SO_2 was also observed behind relief obstacles (Lawrence, 1962), though whether this was related to shelter or not is not clear.

2.4 Adverse Effects of Air Pollution

All forms of life depend on gaseous interchange for their survival, a process perfected by evolution over millennia. But few plants or animals are equipped to cope with the large scale contamination of the air by particulate matter and waste gases which is so widespread in modern industrialised countries. Some of the resulting damage may be reversible, some indeed may be fatal, causing distributional changes in the affected species, and upsetting the ecosystem, with implications thoughout the trophic levels. The most dramatic example of such a change in a related field of study is the link between insecticide spraying and reductions in the number of high level predators (Hoffman and Linduska, 1949).

In terms of plant damage the numerous small openings, or stomata, in the lower surface of the leaf are unselective and allow toxic gases and suspended particulates to enter the interior of the leaf where either acute injury, becoming obvious almost immediately, or chronic injury developing over a longer period, occurs. In the latter case suboptimum growth or a reduction in yields occurs, which may at the same time be almost impossible to attribute to air pollution due to the complexity of other processes operating. In particular, the influence of light, temperature, humidity, carbon dioxide, and soil moisture is important as each of them is itself subject to modification by air pollution. For example, the soil mineral content and acidity can be altered, as can the amount of light reaching the leaf, by gaseous haze. Considerable variation then is only to be expected in sensitivity to pollutants by plant species. The relative susceptibility can be seen in Table 2.6. For those values below about 2 the relevant minimum concentration of SO_2 to cause damage is about 300$\mu g/m^3$ (Sphere, 1974). Among widely found varieties the greatest range of sensitivities occurs among the lichens which are therefore used to reproduce concentration maps for SO_2 (Hawksworth and Rose, 1970, O'Hare, 1974). Such techniques utilise information concerning fatal concentrations to evaluate mean concentrations of SO_2 depending on which lichen species are present or absent. The area covered by O'Hare (1974) matches very closely that of the present study and enables the distribution of mean winter levels of SO_2 to be examined in relation to the relief of the Glasgow Basin, as well as enabling comparison with results achieved using conventional monitoring techniques.

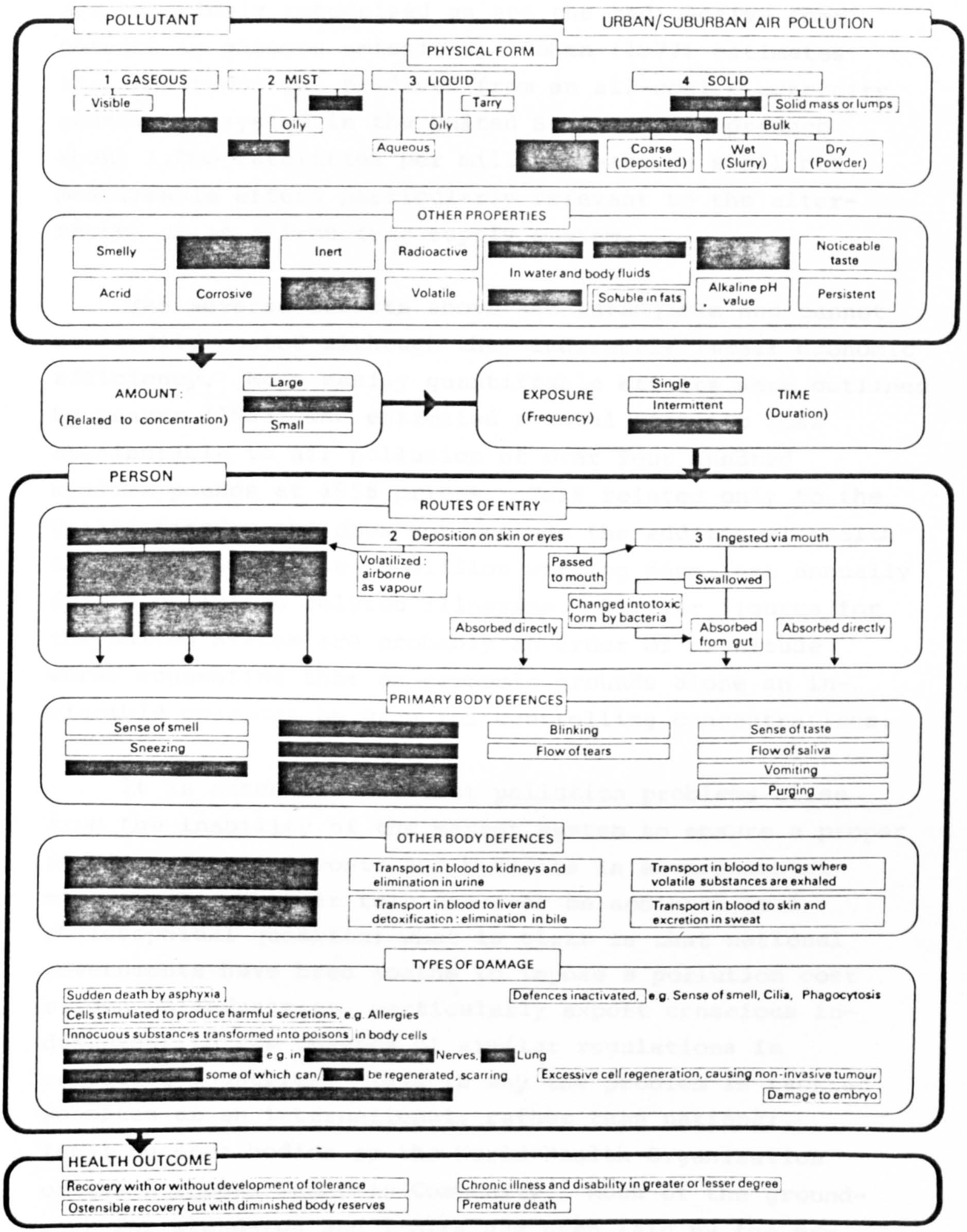
In addition to being sensitive to SO_2 pollution lichens, and vegetation in general, are particularly susceptible to airborne fluoride compounds (Gilbert, 1971). Damage occurs when concentrations exceed about 30 p.p.m. This is most likely close to major industrial sources, a fact which prompted a detailed survey of the study area with reference to possible fluoride damage to vegetation. This was done in association with the infra red aerial survey of the Renfrew Air Pollution Project area. At 24 locations in the county samples of vegetation were collected. None, however, were found to show levels of fluoride in excess of 24 p.p.m., even in the vicinity of Glengarnock Steelworks (Sphere, 1974). However, although fluoride compounds were not found to be significant on the small scale of the present study, it should be remembered that such compounds exert an as yet unknown effect on the composition of the higher atmospheric levels (McCarthy, Bower and Jesson, 1977).

Although evidence of widespread plant damage due to air pollution is not apparent today in Western Scotland there is little doubt that this was not always the case. The dearth of conifers in the Glasgow parks is just one result of past high urban levels of smoke and SO_2. Elsewhere in the world damage to forest resources still occurs. Scheffer and Hedgecock (1955) and more recently Williams et al (1977) have documented damage occurring in the Western United States. In Europe similar damage has occurred in the area around Prague, an enclosed basin with many similarities to the Glasgow Basin, where hillside conifers are affected (Hanibal, 1977).

The problem of 'ceteribus paribus' has bedevilled research into the adverse effects of smoke and SO_2 on human beings. Historically, respiratory diseases were accompanied by poor housing, low income and poor general health levels, which, added to widespread cigarette smoking, made definite conclusions difficult to draw from any given batch of data. Increasingly, however, the available evidence points to the unborn child, young children, and the elderly as that part of the population most at risk. Logan (1953) showed how mortality in newborn infants doubled during the London disaster of 1952, in excess of general mortality patterns. Douglas and Waller (1966) found symptoms of chest congestion to be ten times more prevalent in high pollution areas than in low, for children up to the age of 15, while Carnow (1971) noted an increase in mortality among persons over 55 years of age who were, or had been, exposed to high pollution levels. The difficulties involved in pinning down air pollution as the causative factor in such cases are enormous, since the most susceptible categories are killed, by a combination of illness and environmental factors of which the 'normal' level of air pollution is a component.

Fig. 2.8 shows the complex mechanisms involved in the health aspect of atmospheric pollution. It is at once apparent that a great variety of obstacles must be over come before health damage occurs. Unwanted substances are rejected at several points by the body's natural defence mechanisms. They can be filtered by the nose, trapped by mucus or digested by enzyme action. As each defence is breached the risk of infection or long term injury is increased. The hazard of occupational exposure to pollutants is also frequently underestimated. Selikoff et al (1969) estimated, for example, that an asbestos worker who smokes has 90 times the chance of dying from lung cancer than his non smoking counterpart in

ADVERSE HEALTH EFFECT OF AIR POLLUTION



(after Open University (1975))

Fig. 2.8 Adverse Health Effects of Air Pollution another occupation. The carcinogenic properties of some of the polycyclic hydrocarbons, e.g. benzpyrene, are now widely recognised as are the radioactive components in gaseous emissions. Cohen (1977) estimates that the radon gas produced from an all-coal electricity generating system in the United States would produce about 1,000 fatalities per million years, a small but measureable effect particularly relevant to the alternative of an all-nuclear supply system.

The adverse effects above are intangible and cannot be readily costed although they indirectly impair economic efficiency. More easily quantifiable effects were outlined by Beaver (1958) who estimated a total economic loss attributable to air pollution of over four hundred million pounds at 1958 prices. This related only to the United Kingdom and does not include the additional health cost involved or the 50 million working days lost annually due to pollution related illnesses. Similar figures for the United States are probably an order of magnitude worse suggesting that on economic grounds alone an invincible case can be made for controlling concentrations.

It is often assumed that pollution problems arise from the inability of the market system to ensure a proper costing of social costs and benefits in environmental management. Whether this can ever be achieved is a philosophical question; what is clear is that national governments have been loathe to impose a pollution cost burden on industries, particularly export conscious industries, in the absence of similar regulations in competing countries. This is why the problem is tackled so often at an international, rather than national, level by such bodies as the World Health Organisation or the European Economic Community. Much of the groundwork for standards and limits has been laid by the experience of the United Kingdom in enforcing the Clean Air Acts. It will be seen shortly, however, that unlike the United Kingdom, concentration values, rather than emission standards, are the initial focus of attention of these bodies although, in the imposition of clean air standards, emission legislation is the prime weapon used. Normally, progressively stricter restriction on emissions is envisaged although this is of course dependent on the requisite technology being available to remove and recycle the waste materials prior to their emission into the atmosphere. This implies the continuance of strong economic incentives which must ultimately render air pollution costs excessive relative to control policies.

2.5 Control Policies

In Central Scotland, as in all parts of the industrialised world, there is little doubt that air pollution is detrimental to human health and that a reduction in concentrations would improve health levels. In contrast to this Lucas (1971) suggests that low concentrations of sulphur dioxide may actually have a beneficial effect on agricultural yields by supplying a fraction of the sulphur needs of the growing plants which the farmer supplements normally by the application of sulphate rich fertilisers. Annual dressings of such fertilisers as superphosphate, potash, or sulphate of ammonia average about 20 tonnes/km^2, about twice that occurring through the absorption of SO_2 by soil and vegetation. In this way acid rainfall could be considered a means of supplying plant nutrients and not as a detrimental influence on plant growth. All of this implies, however, the existence of a threshold concentration level below which adverse effects are not apparent. Table 2.6 has already shown that such threshold concentrations are different for each plant species and in such circumstances a much more complex control programme is implied if the often quoted objective of the 60's and early 70's, namely 'the optimum use of atmospheric resources' is to be attempted.

No such threshold has been identified for human beings. While normally healthy individuals may react in a similar fashion to equivalent dosages of air pollutants, related to the body's excretory mechanisms which can cope only up to a certain concentration level, in general, there is a wide range of sensitivities with a massive divergence in susceptibilities in the population at large. Long term ill effects are as yet unknown and it seems reasonable to agree with Mellanby (1967) that there is no safe threshold level, a conclusion rather like that presently being drawn concerning radioactive pollution.

The academic difficulties of establishing a standard for air quality do not eliminate the administrative need

Table 2.6 Relative Susceptibility to damage by SO_2

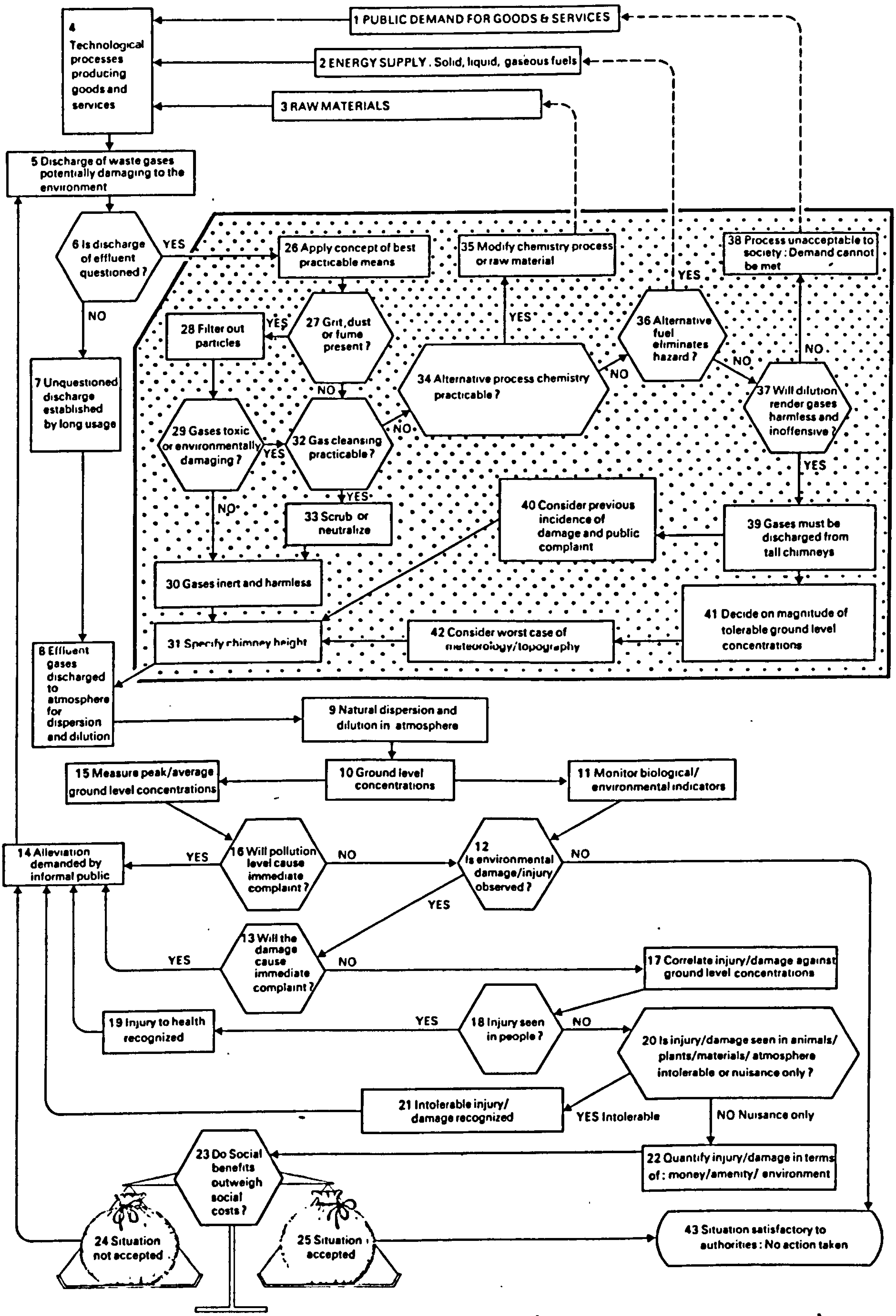
	Susceptible		Intermediate		Resistant
1.0	Lucern	1.6	Cauliflower	1.1-4.0	Gladioli
1.0	Barley	1.6	Sugarbeet	1.8-4.3	Rose
1.1	Rhubarb	1.7	Tomato	3.0	Potato
1.2	Lettuce	1.8	Apple	3.8	Onion
1.3	Oats	2.0	Cabbage	4.0	Lilac
1.4	Rye	2.1	Pea	4.2	Cucumber
1.4	Clover	2.2	Leek	6.4	Celery
1.5	Wheat	2.3	Kale	14.0	Oak
		2.4	Birch	15.0	Privet
		2.5	Plum	7.0-15.0	Pine
		2.5	Poplar	25.0	Apple (flower)
				87.0	Apple (bud)

Source : Open University, 1975

to define one. A target, although with little theoretical basis, is necessary to assess progress, and a wide variety have been adopted throughout the world. The extent and severity of the Scottish air pollution problem can be evaluated by comparing the degree of adherence to some of these standards and accordingly the desirability of new industrial projects assessed at the planning stage. Detailed consideration of this can be seen in Chapter 15, but for now it is worthwhile to examine the origins of some of these recommendations and standards, both at home and abroad.

Probably the first attempt at institutionalised air pollution control was made by Edward I who outlawed the use of 'sea cool' because of its adverse effect on health. A year later, in 1307, he executed a violator of this law (Edelman, 1968). It was not, however, until the passage, in 1863, of the Alkali Act that serious legislative controls were made on the emission of particulates and gases from certain industrial installations. Since then, further updates of the Act in 1906 and 1971, the Clean Air Acts of 1956 and 1968, and the Protection of the Environment Act, 1974, have continued the emphasis on emission restrictions. Tackling the problem on the emission side, without ambient air quality standards has been a peculiarly British approach, and may be partly justified in view of the unreliability of critical concentration values noted above. The control of emissions is regulated either by removing or rendering harmless toxic material according to the concept of 'best practicable means'. The theoretical proceedures involved in this policy are seen in the grey area of Fig. 2.9. Within this framework the only reference to ground level concentrations comes in relation to stack height. Accordingly the only relevant concentration which has institutional relevance seems to be that on which the Chimney Heights Memorandum of 1956 is founded, i.e. that the contribution to ground level concentrations from a chimney shall nowhere exceed $500 \mu g/m^3$ for over three minutes. It will be shown in Chapter 15 that even a chimney 240m high fails to satisfy this requirement for Inverkip Power Station.

AIR POLLUTION CONTROL



(after Open University (1975))

Fig. 2.9 Air Pollution Control

TABLE 2.7 PROPOSED E.E.C. AIR QUALITY STANDARDS

Sulphur Dioxide

Reference Period	Maximum Concentrations ($\mu g/m^3$)	Associated Concentration Suspended Particulates ($\mu g/m^3$)
Year	80 (i)	$>$ 40 (i)
Year	120 (i)	$<$ 40 (i)
October-March	130 (i)	$>$ 60 (i)
October-March	180 (i)	$<$ 60 (i)
24 hours	250 (ii)	$>$100 (ii)
24 hours	350 (ii)	$<$100 (ii)

SUSPENDED PARTICULATES

Reference Period	Maximum Concentrations ($\mu g/m^3$)
Year	80 (i)
October-March	130 (i)
24 hours	250 (i)

(i) Median daily means

(ii) Arithmetic mean

Source: McManus, T. and Reilly, M, (1977)

Table 2.8 Maximum Sulphur Content of Fuel Oils - E.E.C. Directive

Date operative	Type A Gas oil	Type B Gas oil	Fuel Oil
1st October 1976	0.5%	0.8%	--
1st June 1978	--	--	2%
1st October 1980	0.3%	0.5% (i)	--
1st June 1983	--	--	1%
1st October 1985	--	0.5% (ii)	--

(i) Except Ireland
(ii) All countries

Source : as Table 2.7

The choice of the colour grey might be seen as rather appropriate in Fig. 2.9, in view of some of the criticisms of the Act already mentioned in section 2.2 and the flexibility of interpretation afforded by 'the best practicable means' ethos. Tentative conclusions have already been drawn on its effectiveness. Certainly, by concentrating on emissions, the principal effects have been seen in urban areas, where some, such as London, have been obliged to burn fuel with a sulphur content below 1%. Similar restrictions on any petroleum fuel used by the nationalised industries can be imposed by the Secretary of State under the terms of the Protection of the Environment Act, 1974.

International differences in control policies among its member states were considered by the Commision of the European Economic Community as constituting a barrier to free trade i.e. rendering a relative burden on those countries enforcing control legislation. Disparities in the degree of protection given to the population in the various member countries suggested a Community approach to the problem. In February 1976 the Commission (1977) submitted to the Council of Ministers a series of conclusions regarding the linkages between health and air pollution concentrations. The maintenance of smoke and SO_2 levels over 500 $\mu g/m^3$ for several days was identified as resulting in excess mortality especially among the aged and those with cardiovascular or respiratory case histories. Even values over 100 $\mu g/m^3$ sustained over a long term were found to lead to increased infection of the lower respiratory tract and a decrease in maximum expiratory flow rates in children. A directive was issued specifying daily, winter, and annual concentrations which would adhere to these standards, (Table 2.7) and a further directive on the sulphur content of fuel oil was prepared (Table 2.8). This was designed to achieve a gradual elimination of the sulphur rich fuels, a transition which was to be more rapid in zones breaching the above concentration guidelines. It also stipulated that large emitters both inside and adjacent to such zones should switch temporarily to low sulphur fuels, during unfavourable meteorological conditions. The large power stations around Paris are required by law to do this, in any case. Even within the study area Braehead power station has, until its recent downgrading, kept a supply of low sulphur oil for such a contingency. The British Government however, has not yet taken steps to implement fully this directive, particularly as regards emission standards.

A similarity in methods can be noticed between the E.E.C. approach and the United States' Environmental Protection Agency. In both cases ambient air quality standards are set which are enforced by emission controls. There is a notional link between the E.P.A. primary standard and health damage, and secondary standard and environmental damage. The mean annual concentration of SO_2 corresponding to the primary standard is, at $80\mu g/m^3$, the same as that proposed by the E.E.C. Air pollution control regions are expected to satisfy these federal regulations within a fixed time period; once the primary standard is reached the secondary once becomes the next objective. Deterioration of air quality in unpolluted areas is not encouraged and again, like the E.E.C., special provisions exist during atmospheric stagnation periods (Brodine, 1971). Concentration standards are backed up by emission restrictions on new installations and cars. In a number of industries these restrictions are designed to ensure that, with the closing of obsolete plant, new factories will possess the 'best available, economically feasible' control technology. In this context the phraseology is remarkably similar to the 'best practicable means' philosophy outlined for the British experience. Table 2.9 shows the E.P.A. standards along with a similar set issued by the World Health Organisation. The corresponding winter average concentrations for West Central Scotland as calculated by Keddie and Williams (1974) is also shown for comparison purposes. Elements of internal inconsistency are apparent in that the E.P.A. primary standard for smoke on a daily average basis is equivalent to a winter average of $60\mu g/m^3$, while the standard on an annual average equates to a winter equivalent concentration of $125\mu g/m^3$. Nevertheless it is apparent that concentrations in many areas in West Central Scotland must exceed these standards.

TABLE 2.9 W.H.O. AND E.P.A. STANDARDS

	SMOKE ($\mu g/m^3$)				SULPHUR DIOXIDE ($\mu g/m^3$)			
	DAY	(W.C.S Equiv)	Year	(W.C.S. Eq.)	DAY	(W.C.S. Equiv)	Year	(W.C.S. Eq.)
W.H.O. Ill effects (i)	250	60	100	130	250	70	100	115
Long Term Goal	2%>120	45	40	50	2%>200	70	60	70
E.P.A. Primary Standards	0.25% >260	60	75 (ii)	125	0.25% >365	100	80	90
Secondary Standards	0.25% >150	35	60 (ii)	100	0.25% > 260	70	60	70

(i) Levels of Smoke and SO_2 occurring together

(ii) Geometric mean.

Source: Keddie, A. & Williams, F. (1974)

Ambient air quality standards for several other countries are shown in Table 2.10. Those of the U.S.S.R. stand out as being the strictest although Kumar and Djurfors (1977) have pointed out that available data suggests that these standards have not yet been implemented. This illustrates the gulf between the establishment of a plan for control and its successful execution. The elaborate schemes outlined above might seem to suggest that a rapid improvement in air quality is around the corner. In reality, however, gains in controlling emissions from individual sources will be more than offset by the dramatic increase in size and number of such sources. For the British case, in the absence of ambient air standards, in the absence of an adequate rural monitoring network and in the presence of a trend towards large emitters in non urban locations, the most likely outcome is a deterioration in semi rural and rural air quality. This would tend to vindicate the claim made by the National Society for Clean Air (1971) that 'despite geographical differences in climate, relief, and industrial activity, different areas of the country appear to be moving towards the same level'.

TABLE 2.10 COMPARATIVE AMBIENT AIR QUALITY STANDARDS FOR SO_2

MAXIMUM EXPOSURE LIMIT	CANADA		U.S.A.		U.S.S.R.	WEST GERMANY	SWEDEN
	(i)	(ii)	(iii)	(iv)			
½ Hr.	-	-	-	-	-	390	-
1 Hr.	440	880	-	-	150	-	-
24 Hr.	156	286	365	260	-	-	286 (v)
1 Yr.	25	50	80	60	-	-	-

(i) Desirable (ii) Acceptable

(iii) Primary Standard (iv) Secondary Standard

(v) Not to be exceeded more than once a month.

Source: Kumar, A. & Djurfors, S., (1977)

CHAPTER 3

CONDITIONS IN WEST CENTRAL SCOTLAND

3.1 Emissions of Smoke and Sulphur Dioxide

Implicit in any discussion of pollutant dispersal in a given area is some knowledge of the nature and distribution of at least the principal sources. At first sight this might appear relatively straightforward in view of the visual evidence which exists, although experience frequently proves otherwise. The magnitude and type of aerial emissions is, however, for various reasons, not widely publicised by individual industries, nor is it done by the Government body responsible for regulating them, the Health and Safety Executive, formerly the Alkali Inspectorate. Researchers have therefore developed lines of inquiry which either have concentrated on the measurement of air pollution at ground level, or have inferred emission amounts from other data. Using data from monitors in Central Scotland Keddie and Williams (1974) indirectly established a link between emissions and the built up area. This is only to be expected in a region underlain by rich coal deposits where for many centuries coal has been the principal source of energy both for urban industries and commercial and domestic space heating. Though fuel preferences have now changed and coal is less popular as a fuel it has left in Scotland, as elsewhere in the United Kingdom, a historical legacy in the distribution of industry and settlement within the country. It is this juxtaposition of people and pollution which necessitates the management of atmospheric processes in order to obtain the best possible dilution of noxious and harmful emissions (Figs. 3.1 and 3.2).

Largely located below the 125 metre contour, the built-up area of West Central Scotland accounts for about 10% of the area of the region (420 km^2) and includes nearly 2.5 million people. Most emissions, therefore, originate in the Central Clydeside Conurbation, with secondary contributors in the larger Ayrshire or Stirlingshire towns. In these

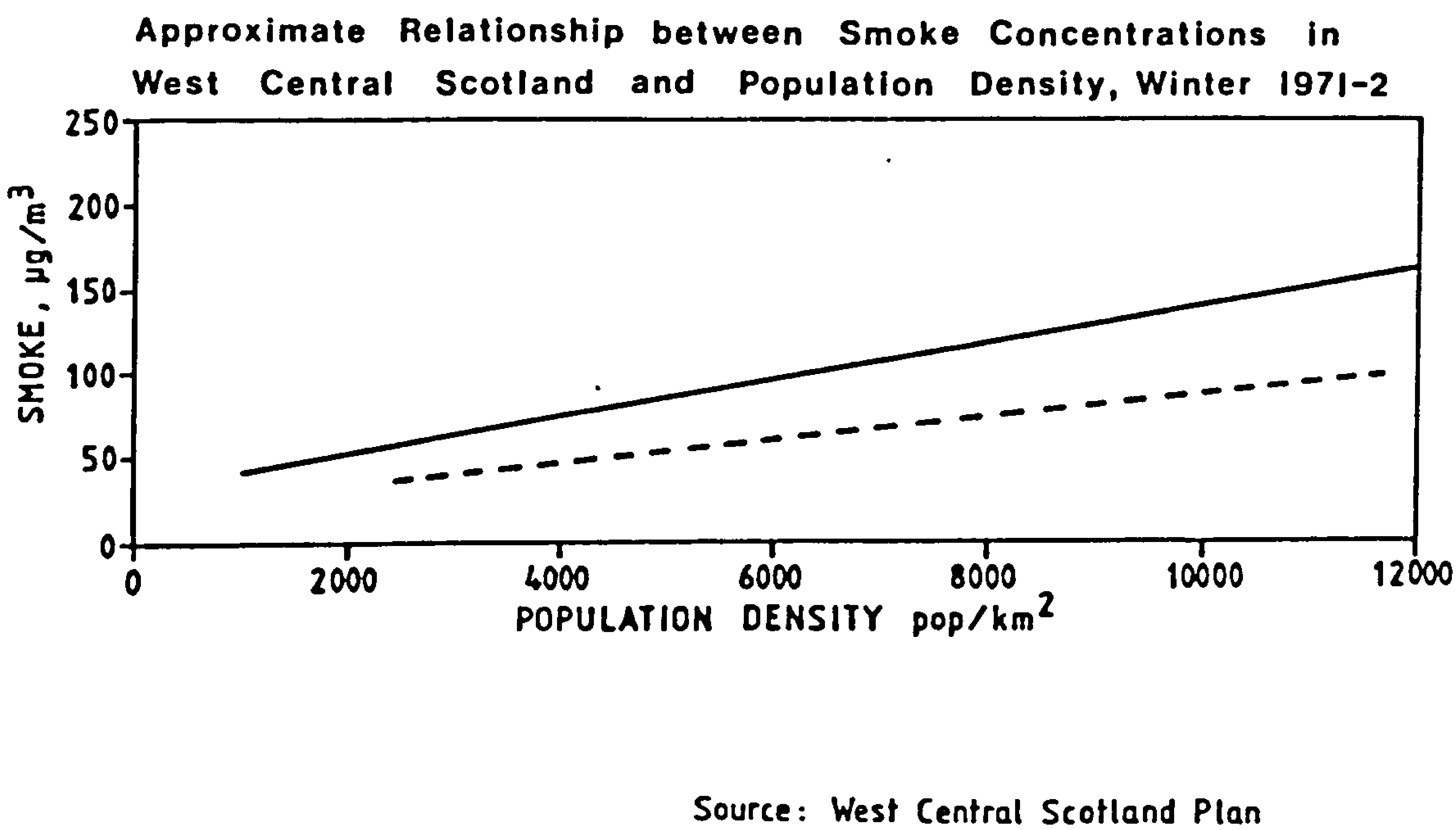


Fig. 3.1 Approximate Relationship between Smoke Concentrations in West Central Scotland and Population Density, Winter 1971-2

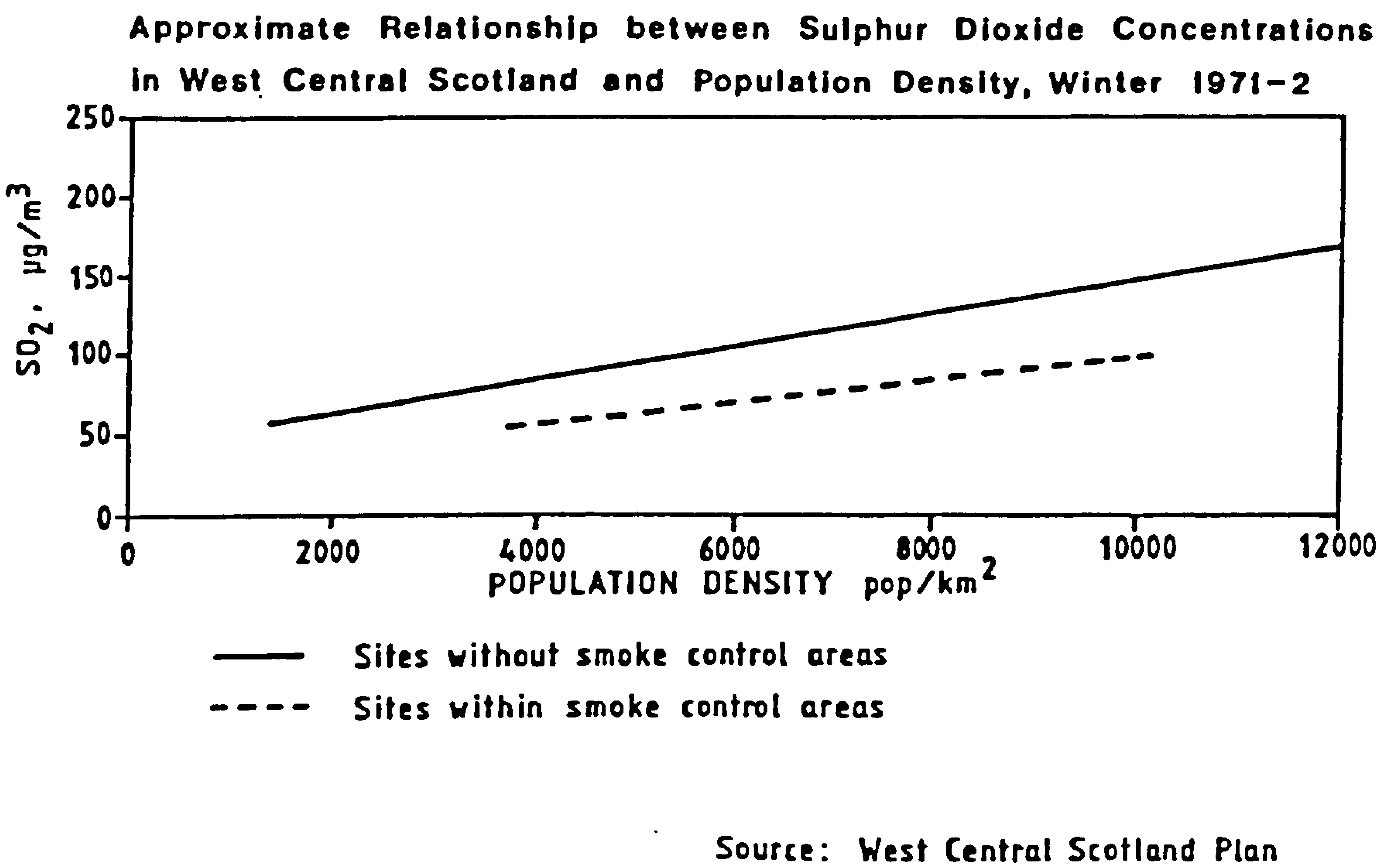


Fig. 3.2 Approximate Relationship between Sulphur Dioxide Concentrations in West Central Scotland and Population Density, Winter 1971-2

areas, and more importantly in West Lothian, domestic coal burning persists. High level SO_2 sources are also important, particularly in the Forth Valley.

A detailed breakdown of emission data is either unpublished or not available (O'Hare, 1974). Such an inventory does exist, however, for the Forth Valley, researched as part of a co-operative project between local authorities and Warren Spring Laboratory. This was derived from returns of monthly fuel consumption figures from some of the larger industrial concerns in the area, such as the South of Scotland Electricity Board, Imperial Chemical Industries, and British Petroleum. This was also done on an annual basis for the smaller domestic, commercial and industrial concerns in the area, enabling the production of an emission distribution matrix on a grid square basis. Initiated over two years after the commencement of the present study in the West, considerable agreement in aims and objectives, as well as in results, is apparent in both studies. (Warren Spring Laboratory, 1974).

While such an inventory would have been very desirable in Western Scotland also, with the exception of one or two large sources, only estimates of emission rates are possible. The most recent of these was made by Ollswang (1972). This was restricted to stationary sources within West Central Scotland, enabling the estimates shown in Table 3.1. These were calculated using standard emission factors which yield pollution amounts based on the amount and type of fuel used, or the quantity of material processed or manufactured. Doubts, however, as to the accuracy of using a method evolved under American conditions must exist, although the totals of 107,456 and 463,247 tonnes p.a. for particulates and SO_2 respectively appear reasonable in relation to the national totals illustrated in Chapter 2.

TABLE 3.1 POULLUTANT EMISSIONS (tonnes/Year), WEST CENTRAL SCOTLAND, 1969-70.

SOURCE	Particulates	Sulphur Oxides	Nitrogen Oxides	Carbon Monoxide	Hydrocarbons	Total
Stationary Fuel Combustion	20,354	240,443	22,645	33,375	8,134	324,951
Coal	19,800	101,917	18,445	32,876	6,872	
Oil	399	138,524	2,975	497	1,244	
Natural Gas	155	2	1,225	2	18	
Power Generation	50,278	217,913	52,483	1,117	746	322,537
Coal Fired Plants	44,027	169,312	44,556	1,114	456	
Oil Fired Plants	152	48,601	7,927	3	289	
Refuse Incineration	406	958	958	480	574	3,367
Iron and Steel Plants	12,195					12,195
Coke Ovens	491					
Blast Furnances	2,744					
Sintering	6,885					
Steel Furnaces	2,075					
Petroleum Refineries	140		2,764	54,543	8,683	66,130
Boilers Process Heaters	140		2,534		144	
Cracking Units			230	54,543	1,009	
Miscellaneous Operations					7,530	
Sulphuric Acid Plants	17	3,933				3,950
Cement Plants	11,230					11,230
Sand Gravel Processing	5,590					5,590
Stone, Clay Processing	7,246					7,246
Totals	107,456	463,247	78,850	89,515	18,137	757,205
% of Total	14.2	61.2	10.4	11.8	2.4	

Source: Ollswang (1972)

3.2 Emissions and Concentration Potential

It is interesting to pause and consider some of the implications of Ollswang's estimates for smoke and SO_2 emissions. In particular, if some simplifying assumptions are made, some appreciation of the concentration potential is possible.

Let it be assumed that calm conditions persist for one week such that no transport of pollution occurs, nor is any removed by the various scavenging processes. Visualise this occurring in the Clyde Valley with 90% of Ollswang's total for West Central emissions of smoke and SO_2 being emitted in this area, and being trapped below a static subsidence inversion at 1,000 metres altitude. It will be seen later that such a scenario of events is not impossible and may well have been responsible for past pollution episodes in the Clyde Basin. Under such circumstances a fixed mass of smoke and SO_2 is injected into a fixed volume of air. If the area involved is 420 km^2 (the built-up area of West Central Scotland) then a mean airshed concentration of several thousand micrograms per cubic metre is obtained for both pollutants viz:

<u>Assumption</u>: concentration in lower 1,000m of air over the built-up area.

	Annual Amount (tonnes)	90% Annual Amount (tonnes)	Daily Emission Rate (built up area)
Smoke	107,456	96,710	265
SO_2	463,247	416,922	1,142

Concentration after 1 day trapping at 1,000m

Smoke	630 $\mu g/m^3$
SO_2	2,719 $\mu g/m^3$

Concentration after 7 days unchanged conditions

Smoke	4,410 $\mu g/m^3$
SO_2	19,033 $\mu g/m^3$

While this is a gross estimation based on several assumptions all of which are unlikely to be true at the same time, it nevertheless, demonstrates an existing potential for alarmingly high concentration levels to be reached during unfavourable meteorological circumstances. Smoke values in excess of 5,000 $\mu g/m^3$ were not uncommon in the late 50's in Glasgow although SO_2 concentrations seldom exceeded 3,000 $\mu g/m^3$. What is important, however, is an appreciation of the magnitude of atmospheric loading of pollutants which occurs in the region. The success which dispersal processes usually achieve results occasionally in the dispersive capacity of the atmosphere being taken for granted. As will be seen later this dispersive capability is a function of several phenomena each of which exhibits a degree of independence of the others. On occasion, therefore, they can all fail at the same time producing a potential situation similar to the one described above. In these circumstances Ollswang's assertion that his figures represent a conservative estimate would result in even more formidable concentrations than those mentioned above.

3.3 Fluctuations in Emissions

Ollswang's estimates present a static picture, exemplified by the dominant role of coal fired power stations for both pollutants. Since the late 1960's considerable advances have been made in minimising particulate emissions and Ollswang's estimate that only 10% of known smoke produced is actually discharged may now be outdated. However, this is not the case for SO_2 and it must be assumed that the bulk of the 463,247 tonnes, together with the other pollutant gases, are discharged directly into the atmosphere. Even so, it should be noted that Scottish coals possess a relatively low sulphur content, averaging below 1%. This compares favourably with a national average of over 1.5% and values in excess of 1.8% for areas such as South west Lancashire (Warren Spring Laboratory, 1972). This goes a long way towards explaining the relatively low levels of SO_2 concentrations observed in Scotland as compared with other parts of the United Kingdom.

Over short periods, some degree of constancy can be assumed for emissions. Schmidt and Velds (1969) discussed the relationship between meteorological factors and SO_2 concentrations over six winters in Rotterdam. In finding that weather variables could account for 92% of the variance in SO_2 concentrations their assumption that emissions were constant over the period seemed to be vindicated. However, a later study by van Dop and Kruizinga (1976) demonstrated considerable variation in emissions over a thirteen year period. Many of the reasons for these fluctuations are apparent when the concentration data for West Central Scotland are examined.

The most regular fluctuation in emissions relates to seasonal factors. Increased emissions from heating plant and power stations contrast with the lower energy demands during high summer. Comer (1976) has remarked on the closeness with which the concentration cycle matches the annual temperature cycle in the study area. The minimum values occur in June, July and August. The peak values for smoke occur in late autumn and for SO_2 in midwinter. The importance of the space heating component in emission quantities is perhaps demonstrated by the strength of this annual cycle for SO_2. It might be expected that SO_2 would be relatively constant due to its high industrial component. This is not so, as will be seen later (Fig. 5.1), and probably demonstrates that the National Survey instruments principally monitor local emissions with a relatively high domestic or commerical heating component. The virtual disappearance of domestic smoke during high summer may further reinforce this conclusions (Fig. 5.1).

Summer pollution values in the area are also affected by the traditional practice of closing all the heavy industries in and around Glasgow for the two weeks annual holiday in July known as the 'Fair Holiday.' Similar shutdowns, occur at different fortnights in July and August at adjoining industrial centres such as Clydebank and Paisley, although the last two weeks in July are by far the most popular. Over a nine year period the two week spell before and after this fortnight showed consistently higher smoke and SO_2 levels, up to 50% for SO_2 and 47% for smoke (Crowe, 1971). Accordingly it is not surprising that Halstead (1958) could comment on the clarity and cleanliness of the air during this period. During the course of plotting the daily concentration values for the three Renfrew monitors it was very apparent that similar, though smaller, effects were noticeable at other times of the year on Public Holidays, further demonstrating emission variability.

It has always perplexed researchers seeking to construct prediction models that similar meteorological conditions at similar times of year rarely produce similar concentrations. A changing emission regime is obviously still apparent. In part this may relate to the particular stage in the economic cycle which is prevailing. The industrial economic cycle is not a regular progression, but a series of booms and recessions which wax and wane according to the managed level of consumer demand. This has been particularly striking in the United Kingdom with its post war record of 'stop-go' economic cycles. Expansionist policies have invariably triggered off a consumer boom, increased imports and led to a balance of payments problem necessitating deflationary action. The ensuing recession dampens demand, increases unemployment and consequently reduces emissions from industrial and commercial sources. By contrast, plants working to full capacity, with overtime or double shift working, obviously have a greater energy demand and emission output.

In general terms the economic indicators show an expansionary period during the early seventies, halted in the wake of the energy crisis of 1974 with a continuing slow recovery from the middle of the decade onwards. As mentioned above it might be expected that emissions, and consequently ground level concentrations, of smoke and SO_2, would exhibit some of these variations. To test this mean monthly values of the two pollutants were regressed against mean monthly averages of Scottish unemployment rates. For the case of smoke this was not found to be sensitive to unemployment. A correlation coefficient of 0.06 was obtained, significant at 69%, hardly indicative of any relationship between the two. Sulphur dioxide concentrations yielded, by contrast, a correlation coefficient of 0.42 against monthly unemployment, significant at the 99.9% level, which strongly suggests that air pollution by SO_2 is strongly influenced by the vagaries of the economic cycle. It would appear reasonable to conclude that while smoke concentrations reflect domestic emissions which are non-sensitive to economic influences, SO_2 emissions appear to fluctuate markedly in response to the level of demand prevailing in the national economy. (Concentrations refer to Linwood).

Emission changes can also be accounted for by changes in consumer fuel preference. This has closely followed the extension of smoke control policies. Studies by Warren Spring Laboratory (1972) indicated that in 1960 as many as 70% of the inhabitants in newly designated zones selected smokeless fuel, as against only 25% ten years later. The balance was accounted for by gas, oil, and electricity, fuels having a considerably lower sulphur content. At the same time as this, the sulphur content of gas has largely been eliminated by the conversion of supplies from town gas to natural gas. Garnett and Read (1972) have observed the effects of these changes on peak smoke and SO_2 values in Sheffield, and similar reductions are apparent in Glasgow.

In addition to changes in the magnitude of emissions continually occurring changes in the distribution of sources are apparent. For example, the consumer resistance to smokeless fuel mentioned above has led to an increased demand for the main alternative, electricity. To meet this demand efficient new generating capacity has been constructed and smaller, obsolete plant closed down. This has produced a continually occurring relocation of major sources of SO_2. Due largely to this increased generating capacity provided by Hunterston B and Inverkip the South of Scotland Electricity Board was able to decimmission Yoker and Clydesmill Power Stations during the period, and Dalmarnock in the year following the study period. Braehead, the last of the older stations, was progressively downgraded and formally put on a reduced operations capability in Spring 1978. There is at present no coal burning power station in Western Scotland.

With such fundamental variations in the amount, pattern, height and nature of emissions, attempts at establishing relationships between any two sets of variables almost always involves a considerable degree of 'noise', which obscures many of the relationships undoubtedly existing. The combination of a complex emission environment interacting with a complex meteorological environment is thus a major cause of the great variations in ground level concentrations which are the basis of almost all air pollution studies.

3.4 Ground Level Concentrations of Smoke and Sulphur Dioxide

As might be expected from a body charged with environmental improvement based on smoke control, Warren Spring Laboratory's National Survey exhibits a marked urban bias. This was more clearly so in the past and explains in part the strong relationship between pollution and population density shown in Figs. 3.1 and 3.2 which is a function of the dearth of rural monitoring sites. At the commencement of this project in 1971, 42 monitors existed in the entire study area. In addition four sites in Lanarkshire and one at Kilbirnie in Ayrshire measured smoke only. Naturally, the vast majority of monitors were located in the Glasgow area. Dumbartonshire and Stirlingshire had only token coverage and no coverage at all was apparent on the Ayrshire coast. Considerable expansion has occurred since then and the fifty three stations recording in 1972/73 have been further augmented by the installation of monitors at Ayr, Kilmarnock, Inverkip and Greenock as well as the three connected with this project at Linwood, Erskine and Lochwinnoch (see Fig. 1.1). Progress is also apparent to the east of the city, largely due to the expansion of the Forth Valley Survey. For this sister study data has been utilised from 41 monitors, many of them specifically installed for the Survey. Unfortunately some have already ceased operating but many remain useful for studies centred further west. In particular the relatively recent installation of a total sulphur monitor at Garbethill in the Cumbernauld Gap will hopefully provide detailed information on pollution interchange between east and west in the future. Thus, by providing SO_2 concentrations on a five minute or hourly basis, the flux of SO_2 from the baseload power stations of the Forth Estuary will be able to be quantified more accurately.

In view of the general inadequacy of the Scottish network the construction of a distribution map for smoke or SO_2 concentrations is subject to gross errors in interpolation. Clifton et al (1959) maintained that to convey the pollution picture accurately required a network of sampling sites on a one kilometre grid basis.

This is neither practical nor desirable and is not even achieved in central Glasgow. More recently, however, Marsh and Foster (1967) calculated correlation coefficients between annual SO_2 and local fuel consumption. No significant difference was found to exist between values obtained with monitors on a 1 kilometre grid network, and those on a 2 kilometre grid square density. It would thus appear that monitors are reasonably representative of local low level sources up to 2 kilometres distant. On this basis Comer (1976) concludes that while Glasgow is adequately monitored, much of rural Western Scotland is completely lacking in pollution data. Auxiliary information is obviously required for such areas and Keddie and Williams (1974) used the now familiar one of population density to produce the choropleth maps shown in Figs. 3.3 and 3.4.

The principal advantage of such maps is that they provide a categorical zonation of pollution. With an appropriate selection of class intervals coincidence with international standards can be achieved. In this case the World Health Organisation's short and long term aims, and the U.S. Environmental Protection Agency's primary and secondary standards can be related to the plotted winter averages. Equivalent concentrations to these values for West Central Scotland have already been established (see Table 2.8). The E.P.A. daily primary smoke standard is equivalent to a winter concentration of 60 $\mu g/m^3$ in this area, meaning that zones 3 and 4 exceed this. Central Glasgow also exceeds the primary standard for SO_2. For both pollutants the 'ill effects' level of the W.H.O. are breached in large parts of the conurbation and a few outlying towns. Only zones 1 and 2 would have satisfied both the long term goal and E.P.A. secondary standards during the winter under study.

Distribution of Smoke in West Central Scotland, Winter Averages for 1971-2

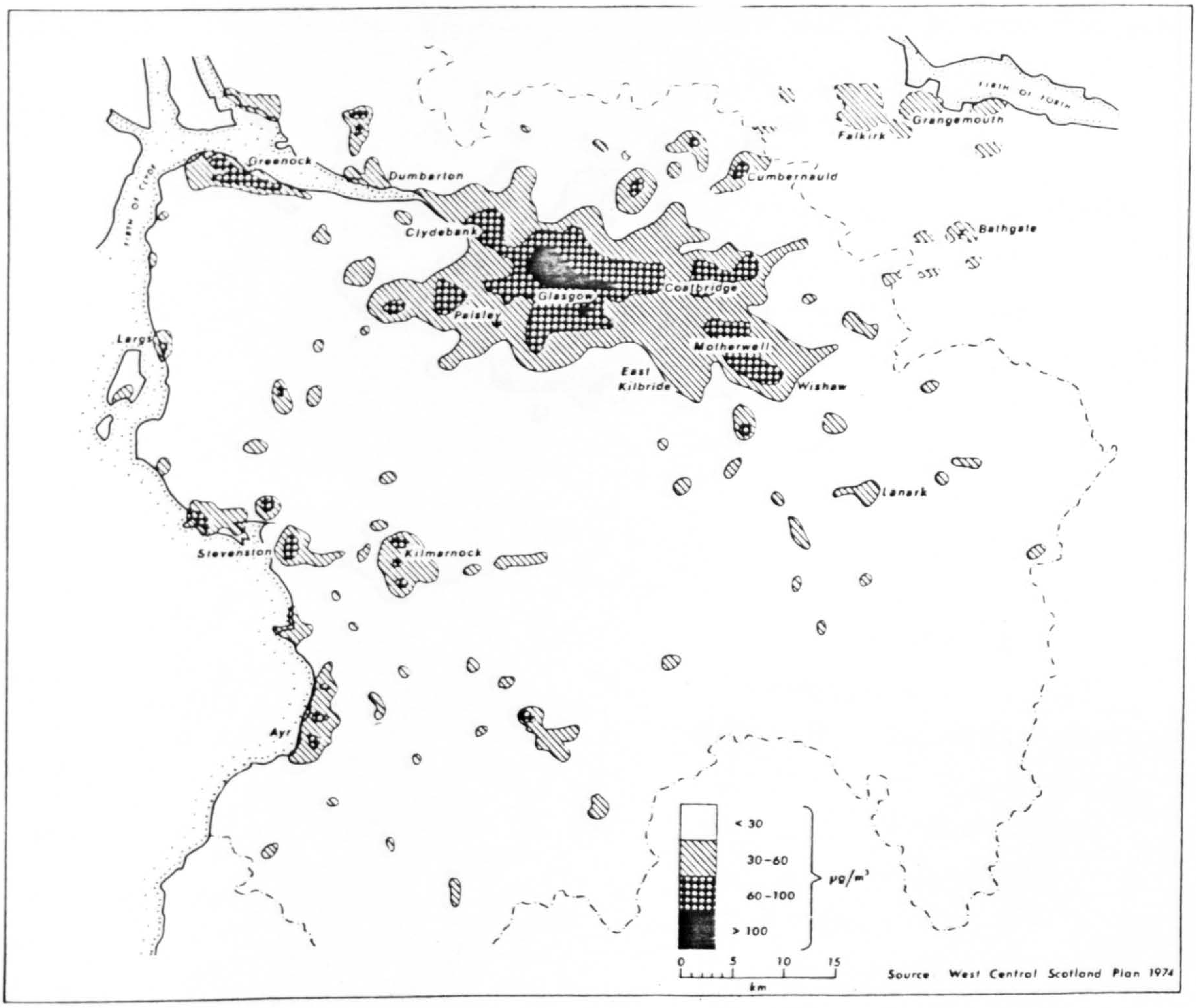


Fig. 3.3 Distribution of Smoke in West Central Scotland, Winter Averages for 1971-2

Distribution of Sulphur Dioxide in West Central Scotland, Winter Averages for 1971-2

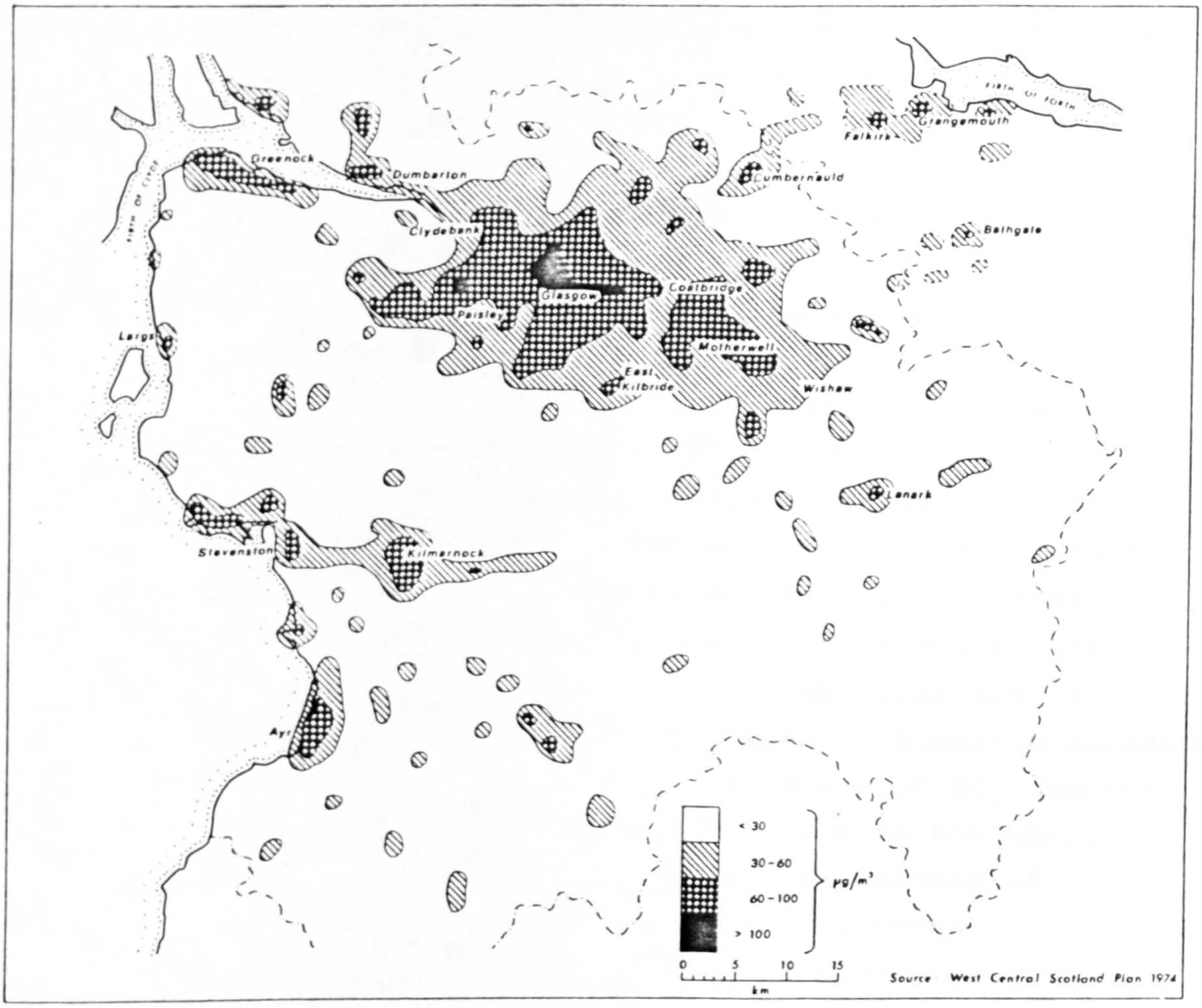
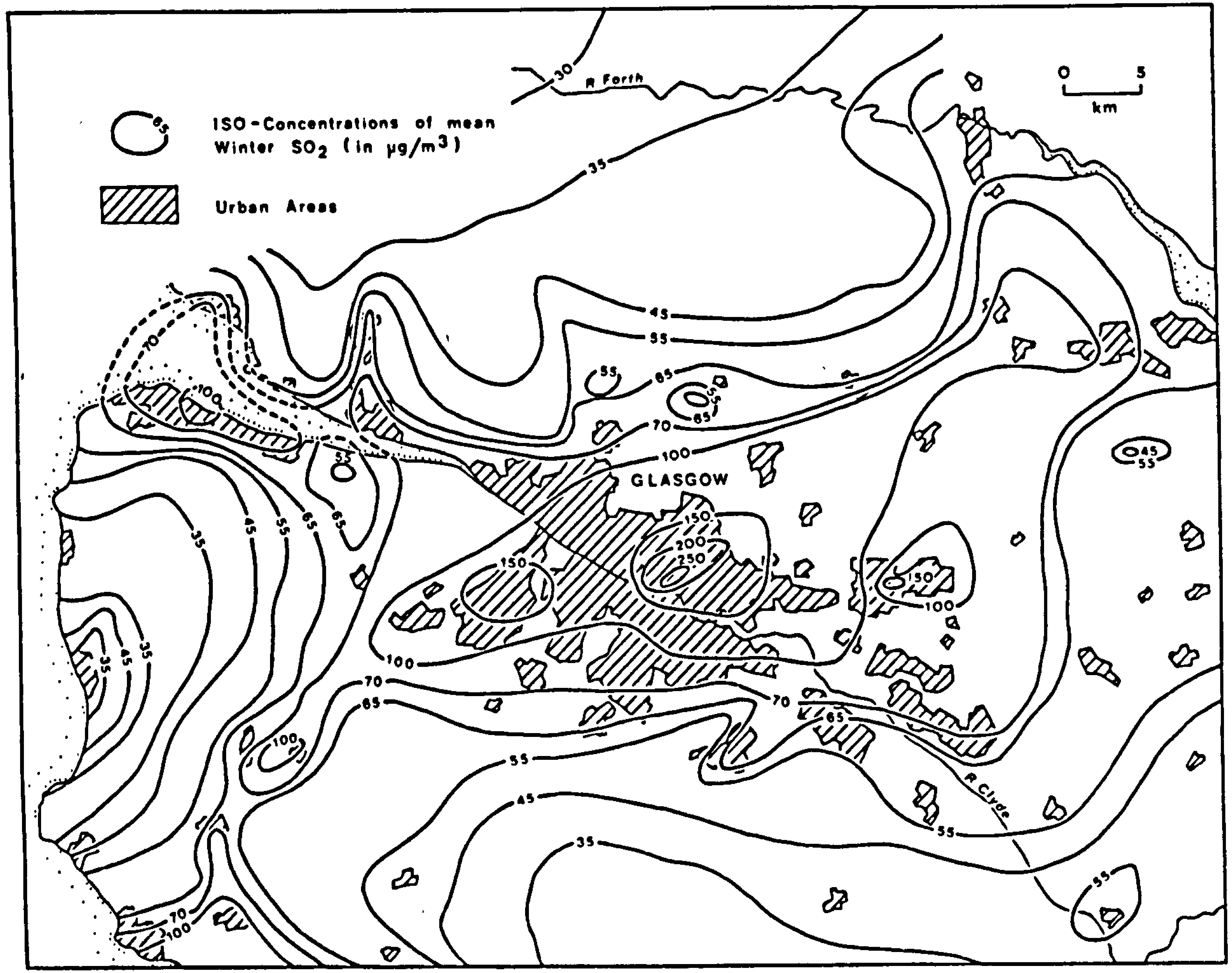


Fig. 3.4 Distribution of Sulphur Dioxide in West Central Scotland, Winter Averages for 1971-2

The major disadvantages of the maps relate to their inability to show the pollution gradients and so illustrate the role of relief and the transport of material by wind action. For such considerations as these a more detailed isopleth map is required. Out of necessity resort has been made to indirect data sources in order to obtain a greater coverage of rural areas. The distribution of lichens of varying sensitivities to SO_2 was considered by O'Hare (1974) and using zonation techniques developed by Hawksworth and Rose (1970) he mapped winter levels of SO_2 throughout West Central Scotland (Fig. 3.5).

It would appear from O'Hare's map that the relationship between concentrations and urbanisation levels strengthens as population density increases. This suggests that the greatest contribution to the concentrations comes from local or low level emissions. Confirmation of this hypothesis was sought from other research, and the data from the Forth Valley Survey proved eminently suitable for this purpose. Table 3.2 provides a breakdown by source type for several monitors in the area. Invariably domestic coal accounts for over 90% of the smoke concentrations observed with commercial and industrial emissions fairly insignificant. Domestic emissions are even responsible for a sizeable share of SO_2 concentrations. Scattered local sources, such as the small mining towns of West Lothian, appear as islands of pollution on the maps and highlight urban-rural differences in smoke and SO_2 levels. According to Warren Spring Laboratory (1972) average winter smoke and SO_2 on a national basis was 95 and 98 $\mu g/m^3$ for urban locations in 1970/71. Comparable rural figures were 33 and 23 $\mu g/m^3$ respectively. However the Scottish figures exhibit an even larger disparity. Urban levels of smoke and SO_2 averaged 116 and 108 $\mu g/m^3$ respectively while rural levels were 30 and 22 $\mu g/m^3$. It has been suggested by Nicholson and Keddie (1972) that this larger difference for Scotland relates to the extent of large, open spaces in Scotland which permit better dilution in rural areas.

ISO-CONCENTRATIONS OF MEAN WINTER SO_2



Source: O'Hare (1974)

Fig. 3.5 Mean Winter Concentrations of SO_2 Based on Lichen Distribution

TABLE 3.2 CONTRIBUTIONS BY SOURCE TYPE TO OBSERVED SMOKE AND SO_2 CONCENTRATIONS FOR WINTER 1974/75 in EAST CENTRAL SCOTLAND.

STATION		SMOKE						SO_2					
		DC	%	SSF	%	C/I	%	DC	%	SSF	%	C/I	%
WSL	I	23.0	96	0.5	2	0.5	2	8.5	25	2.0	6	23.5	69
WSL	2	16.0	94	0.5	3	0.5	3	6.0	22	1.5	5	20.5	73
WSL	3	14.5	94	0.5	3	0.5	3	5.0	19	1.5	6	19.5	75
WSL	22	16.0	94	0.5	3	0.5	3	6.0	24	1.5	6	17.5	70
SC	1	67.5	98	1.0	1	0.5	1	24.5	54	2.5	6	18.0	40
L	I	39.5	99	0.5	1	0.0	0	14.5	58	1.5	6	9.0	36
BR	2	42.5	98	0.5	1	0.5	1	15.5	50	1.5	5	14.0	45
G	2	31.5	93	2.0	6	0.5	1	11.5	27	5.5	13	26.0	60
G	3	23.0	92	1.5	6	0.5	2	8.5	19	4.0	9	32.5	72
G	4	27.0	93	1.5	5	0.5	2	10.0	24	5.0	12	26.0	64
G	5	25.0	92	1.5	6	0.5	2	9.0	18	4.5	9	35.5	73
G	6	24.0	92	1.5	6	0.5	2	8.5	20	4.5	11	29.0	69
G	7	35.0	94	2.0	5	0.5	2	13.0	26	6.5	13	30.5	61
F	5	36.0	91	2.0	5	1.5	4	13.0	13	6.5	7	77.0	80
F	6	36.5	91	2.0	5	1.5	4	13.0	13	6.5	7	80.0	80
SC	8	31.5	93	2.0	6	0.5	1	11.5	24	5.5	11	32.0	65
SB	2	28.5	95	1.0	3	0.5	2	10.5	24	2.5	6	30.0	70
SB	3	61.5	98	0.5	1	0.5	1	22.5	57	2.5	6	14.5	37
M	1	29.0	94	1.0	3	1.0	3	10.5	19	2.5	5	41.0	76
AL	6	25.0	94	0.5	2	1.0	4	9.0	14	1.0	2	54.0	84
KF	17	18.0	94	0.5	3	0.5	3	6.5	18	1.5	4	29.0	78
BL	1	24.0	96	0.5	2	0.5	2	8.5	30	2.0	7	18.0	63

DC - Domestic Coal C/I - Commercial/Industrial Fuel

SSF- Domestic Solid Smokeless Fuel

Source: Forth Valley Survey (1976)

Dispersal of pollution is achieved principally by wind action, the effect of which is apparent on both sets of maps. In particular the extension of the higher concentration values in a north easterly direction across Central Scotland indicates the effect of the prevailing south westerly wind in transporting the pollution plume from Glasgow prior to its dispersal. Less frequent transport of material in the opposite direction by a north easterly wind is also significant. This is undoubtedly due to the fact that such winds frequently occur under anticyclonic conditions meaning that while they only occur about one sixth of the time, they are not conducive to pollutant dispersal.

Where isopleths are closely drawn the influence of relief is apparent. In particular the constraints on dispersal imposed by the shelter afforded by the overlooking plateaux are clearly noticeable with pollution isopleths following the lines of generalised contours, especially on the slopes of the Campsies and Renfrew Heights. Isopleths are particularly close together at the major relief gaps mentioned earlier and a general line of pollution movement from the Lochwinnoch Gap across the Forth-Clyde watershed is apparent. The strong gradients at these gaps indicate a considerable flux of smoke and SO_2 and it can reasonably be assumed that the import of effluent from distant sources in Ayrshire and the Forth Valley occurs by the channelling of the airflow through these gaps. Evidence for this can be seen in Chapters 7 and 15. It can also be noted from O'Hare's map that nowhere in the region does unpolluted air occur; even in the mountainous north west a lichen distribution characteristic of winter levels in excess of 30 $\mu g/m^3$ is in evidence.

Considerable differences are apparent between the two SO_2 maps with, in general, O'Hare's values being higher than those of Keddie. This has resulted in a slight variation of the orientation of the zone of highest concentrations. With O'Hare the area in excess of 100 $\mu g/m^3$

extends from west of Kilbarchan to Falkirk, showing a distinctive south-west to north-east trend. On the other hand, Keddie and Williams' comparable area is restricted to central Glasgow, with a small outlier in Paisley, and trends north-west to south-east along the Clyde Valley. If, however, O'Hare's concentrations were reduced somewhat a truncation of this area to the east of the watershed would occur, and a distribution pattern more closely matching Keddie's would result. This would seem a reasonable conclusion in view of the drawbacks in comparability between the two maps described below.

Detailed comparison between the two maps is not possible for several reasons. Firstly, they relate to slightly different time periods. But more importantly, O'Hare's map relates to SO_2 concentrations which prevailed in the past, either a few or several years ago, and which was then responsible for the lichen distribution at the time of survey. In other words, during falling SO_2 levels, the time lag before recolonisation makes temporal comparisons impossible. What is clear, however, is that the concentration pattern, like the emission pattern, is undergoing fundamental change, rendering any map of concentrations obsolete even before it is published. This, in turn, indicates the achievement of at least a modicum of success in reducing the concentrations of pollution experienced at ground level.

3.5 Smoke and Sulphur Dioxide Trends

In line with the national trend shown in Chapter 2 smoke and sulphur dioxide concentrations have shown a considerable reduction during the past twenty years. The period of most rapid reduction came during the early sixties and, though some degree of levelling out is apparent since then, progress continues. This is largely due to the continued decline in domestic coal consumption. This fell by 70 per cent between 1962 and 1978 as against an overall reduction of 40 per cent for the coal market as a whole (H.M.S.O., 1979).

The most spectacular changes naturally occurred where concentrations were formerly highest, in the central Glasgow area. If the average of the five central monitors is used (Glasgow 20, 44, 47, 51 and 52) then typical winter smoke figures of 435 $\mu g/m^3$ in 1961/62 give way to values of 48 $\mu g/m^3$ for 1978/79. This is a reduction of 89 per cent and brings Glasgow city centre below the E.P.A. primary standard. The corresponding decrease in mean summer concentrations, from 88 $\mu g/m^3$ to 21 $\mu g/m^3$ (in 1976/77) is considerably less and tends to suggest that the reduction in domestic emissions has not been accompanied by a corresponding reduction in industrial emissions.

The reduction in smoke concentrations greatly exceeds the decrease in domestic coal consumption. This can be explained partly by improved technology which removes particulate matter prior to discharge. However, it may also relate to the improved dispersive capability of the lower atmosphere. As the opacity of the air near the ground in Central Scotland, has decreased more solar radiation can reach the surface, inhibiting low level inversion formation during daylight hours. To some extent the opposite effect may occur during darkness when nocturnal inversion frequency is probably increased slightly. However, the net effect would appear to suggest that daytime improvements exceed any increased nocturnal inversion incidence and on balance the trapping of pollutants is slightly reduced as are ground level concentrations. A system of positive feedback has occured.

Visibility is highly susceptible to the presence of smoke in the atmosphere. Whereas under normal circumstances fog will only occur when relative humidity is almost 100%, the existence of smoke reduces this figure to 95% and Plant (1967) has observed fairly thick winter fogs in the Glasgow area with relative humidities as low as 75%. Accordingly, 'dry' fogs, periods when visibility is below 1 kilometre and relative humidity below 95%, are a fairly good index of atmospheric pollution, particularly by smoke. McKellar (1969, 1979) has shown a substantial reduction in the number of hours of fog during light wind periods in the area in recent years. He has furthermore obtained a correlation coefficient of 0.87 between the duration of dry fogs and winter smoke levels at Paisley 5, significant at the 99% level. As Fig. 3.6 shows, the phenomenon has now all but disappeared, although climatic conditions are such in the area that fog will still occur about 10-20% of the time with winds below 3 knots, particularly in winter, regardless of how pure the atmosphere is.

Much of the amelioration is smoke levels can be attributed to the policy of progressive smoke abatement initiated by the Clean Air Act of 1956. By 1976 350,000 houses, some 42% of the region's housing stock were subject to smoke control regulations (Comer, 1976). In fact four of the first five Scottish burghs to achieve 100% coverage by smoke control orders are in the study area. East Kilbride, Coatbridge, Bearsden, and Kilmarnock all achieved this by late 1973. Progess in Glasgow had achieved a 74% coverage rate by this time but since then stagnation is apparent. Only three small wards in the city's West End have been designated since 1973 and no progress at all is apparent since then (Fig. 3.7). In some ways this is understandable. The peripheral zones were easiest to complete, corresponding, as they do, with the sprawling post war housing schemes of uniform, medium density type housing when conversion to alternative fuels

Fig. 3.6 Trends in the Incidence of Fogs at Glasgow Airport;Winters 1955-6 to 1978

SMOKE CONTROL ZONES IN GLASGOW

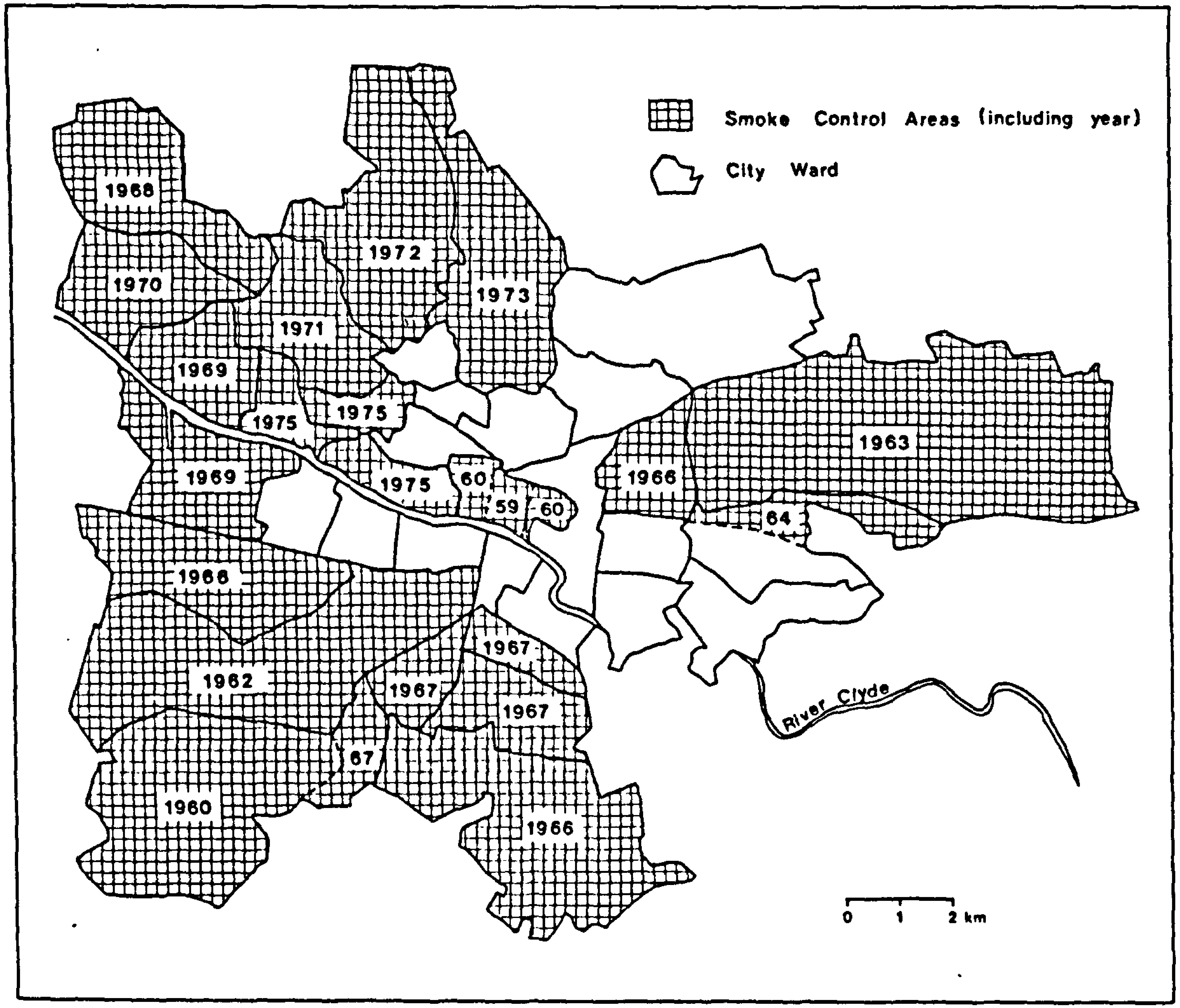


Fig. 3.7 Smoke Control Zones in Glasgow

was relatively straightforward. The older areas of decaying tenemental property nearer the city centre were much more slow to adopt smoke control measures. Current policy seems to be to allow redevelopment to achieve control objectives, as for example in the tongue of wards in the Glasgow East End Renewal scheme. The comprehensive redevelopment of this and other such areas will include their designation as smokeless zones and new housing stock will be designed to accommodate this.

It is much easier to build new housing stock than to create new employment for the tenants. A feature of modern day Glasgow, therefore, is the existence side by side of modern housing and obsolete industry retained despite air pollution to retain employment for as long as possible. In some cases these are uncompatible, as for instance with the Norrit-Clydesdale factory in the east of the city. Plate 1 shows how adjacent high rise flats are subjected to unacceptable pollution levels under easterly wind conditions. Less striking examples can be seen in many parts of the city.

Other priority areas in West Central Scotland include the remaining outer areas of Glasgow not under smoke control and the residential centres of many other towns in the region. Almost total smoke control is projected for the region by 1980 although this certainly will not be achieved until well into the 1980s. Before this, however, Warren Spring Laboratory expect winter smoke concentrations to fall below 6o $\mu g/m^3$ thoughout Scotland. Fig. 3.8 which shows winter values for four selected stations including some of the most polluted, suggests that this target has now been realised. It should be noted however, that high smoke pollution episodes will continue to occur in unfavourable meteorological circumstances.

The success story for smoke concentrations does not find a sequel with regard to SO_2. Only in the city centre has a marked deminution occurred. Mean winter values at the 5 central monitors averaged 232 $\mu g/m^3$ in 1961/62 against 100 $\mu g/m^3$ in 1978/79, a reduction of some 57 per

Plate 1

Living with air pollution:

the Norrit – Clydesdale works in Glasgow

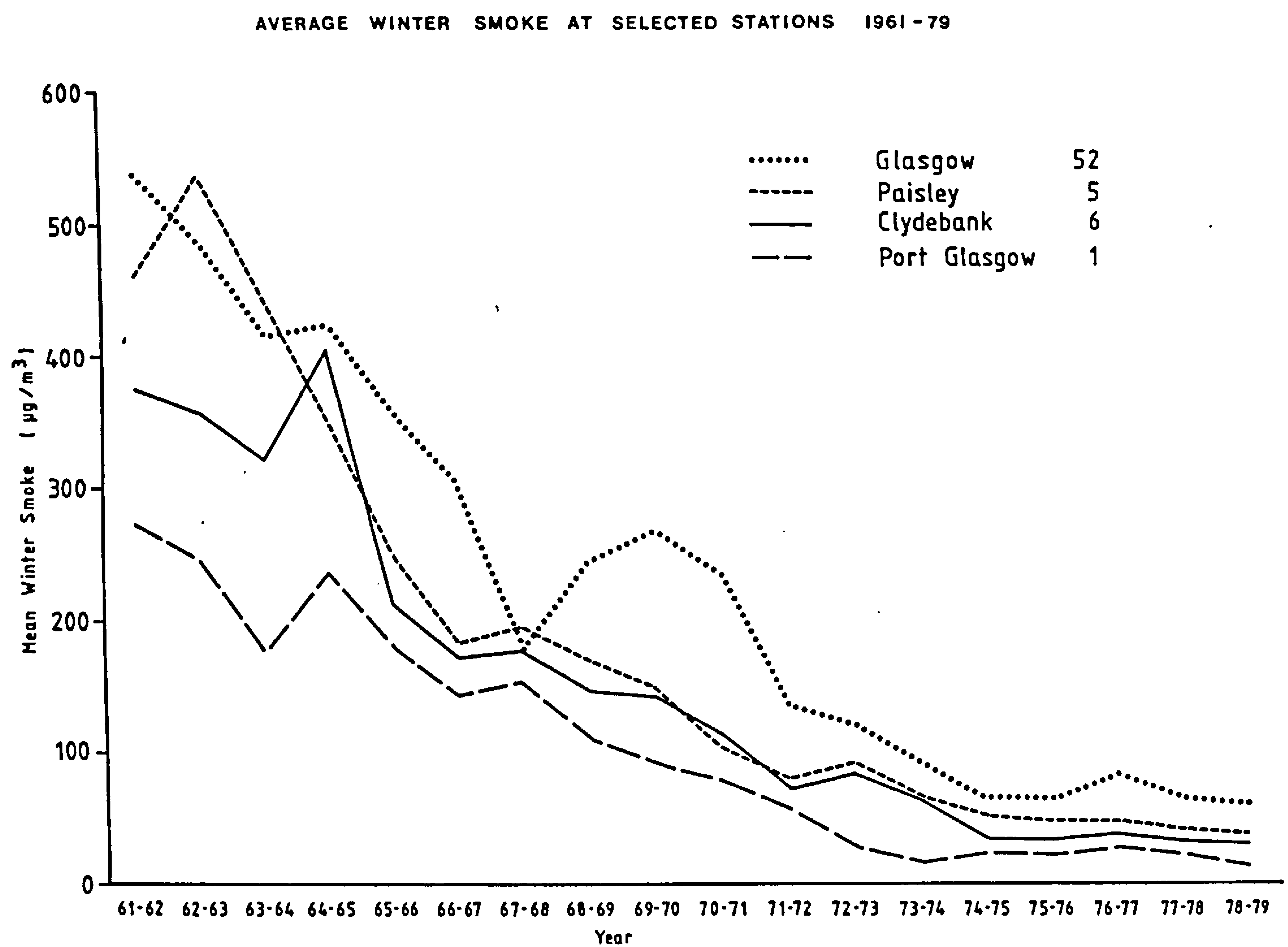


Fig. 3.8 Average Winter Smoke at Selected Stations 1961-79

cent. This is considerably less than that observed for smoke. Outside the city the decrease is less marked, with some stations e.g. Grangemouth 2 and Port Glasgow 1 even registering a slightly rising trend for at least a substantial part of the 18 year period. All this tends to imply a lack of real progress in the reduction of emissions in general, with an industrial emission category which continues to increase. Many of the changing trends in industrial location can be deduced from the figures for the various locations. Most worrying appears to be the increasing SO_2 levels at some semi rural locations in the area. This is in direct contravention of the E.E.C. directive (Commission, 1977) which specifically prohibited the reduction of urban SO_2 levels by the contamination of previously relatively unpolluted rural areas.

Representative data is scarcer for SO_2 than for smoke and the intermittent operation of SO_2 monitors has left only a few stations with an unbroken run of data, over the last fifteen years. The position has been further exacerbated by the closure of the prime central monitor in Glasgow, Glasgow 1, since 1971. If, however, the same four stations are selected as for smoke then many of the trends indentified above are apparent. Outside the conurbation concentrations have remained relatively static and a levelling off in the reductions are apparent, even for Glasgow and Paisley (Fig. 3.9). It seems likely though that winter SO_2 levels will exceed 60 $\mu g/m^3$ on average in Glasgow city centre and possibly also in some high density residential areas for some time to come, largely due to the effects of oil combustion.

That a downturn in urban SO_2 values has been accompanied by a reduction in the severity of pollution 'episodes' is confirmed in Fig. 3.10. The duration and severity of freezing fog is important in this case, as will be seen later, but it should not be assumed that high pollution episodes are exclusively a winter phenomenon. As will be later demonstrated an increasing incidence of summer pollution 'episodes' is apparent, particularly, during 'heatwave' conditions. Nevertheless, the level of peak concentration, regardless of time of year, is con-

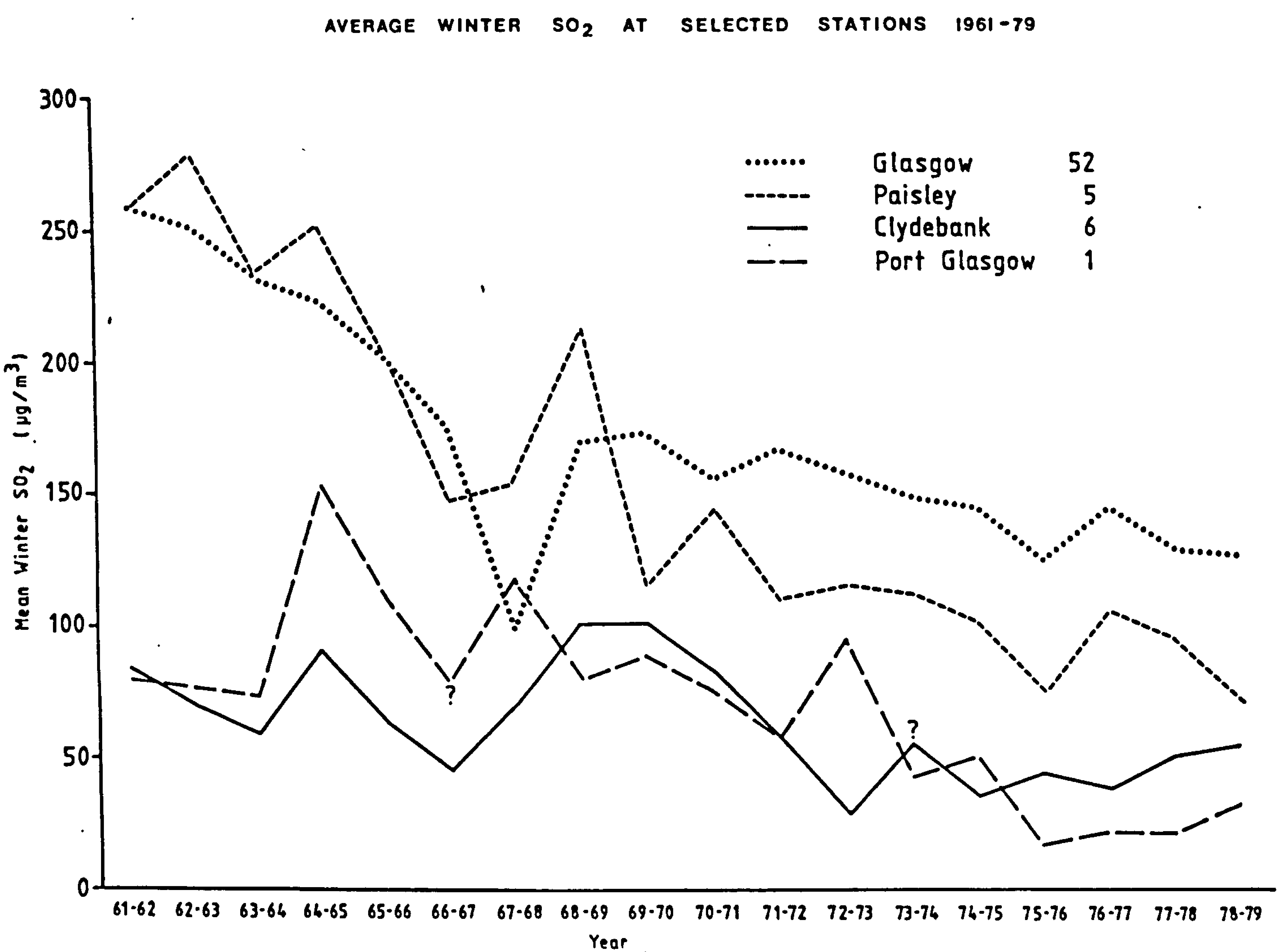


Fig. 3.9 Average Winter SO_2 at Selected Stations 1961-79

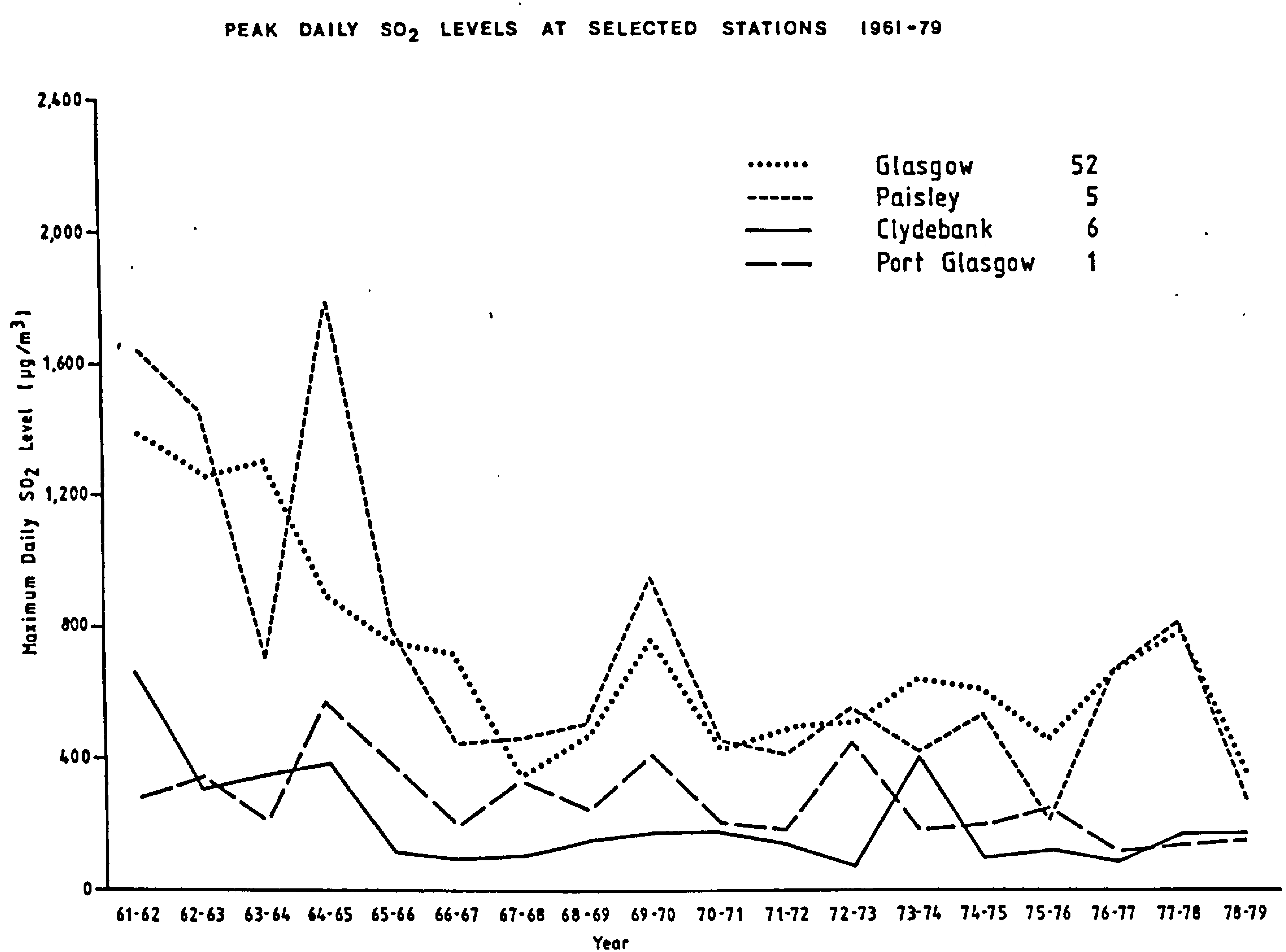


Fig. 3.10 Peak Daily SO_2 Levels at Selected Stations 1961-79

tinuing to fall to a base level somewhere between 100 and 200 $\mu g/m^3$. This is not to imply that on certain occasions levels in excess of those causing a potential health hazard will not occur. As has been shown in Chapter 2 such a potential exists and under certain meteorological conditions might be expected to give rise to a considerable departure from the various trends and figures mentioned above.

In summary, then, it would appear that the historical problem of smoke pollution has become of secondary importance relative to pollution by sulphur dioxide. This is a result of the changeover from coal to other fuels and the extension of the smokeless zone policies required by the Clean Air Acts. These policies, however, are not resolving satisfactorily the problem of SO_2 pollution which remains significant despite marked improvement in heavily polluted areas. Thus, although the very high values of the past are unlikely to recur, SO_2 emissions continue to persist at a high level, and the avoidance of potentially dangerous concentration levels is achieved by a combination of meteorological good fortune and the export of the problem to other parts via high chimneys. For this reason, the emission characteristics of new industry is very important and a continuing monitoring programme in West Central Scotland remains necessary.

CHAPTER 4

THE DATA, ITS ANALYSIS AND LIMITATIONS

4.1 Atmospheric Pollution Data

In conjunction with the National Survey of Atmospheric Pollution, under the supervision of Warren Spring Laboratory, smoke and sulphur dioxide concentrations are measured, on a daily basis at almost all of the sites outlined in Chapter 3 in West Central Scotland. The technique employed is described in detail in British Standard 1747 Parts 2 and 3 (1969) and also in the Instruction Manual provided by Warren Spring Laboratory (1966). Essentially it involves passing a known volume of air through a filter which removes suspended particulate matter and then bubbling the same sample through a dilute solution of hydrogen peroxide in a Drechsel bottle where any sulphur dioxide present is oxidised to sulphuric acid. Using a calibrated reflectometer the darkness of the filter provides a value for smoke concentration while a simple titration with a standard alkaline solution gives the concentration of SO_2 in the sample of air utilised.

Several considerations influenced the selection of this technique as the standard method, apart from it's wide-spread use prior to the 1956 Clean Air Act. The principal need then, was to utilise the simplicity of the reflecto-meter for measuring the all-important smoke values. Simultaneous SO_2 measurement could also be achieved with the low cost apparatus. The system furthermore could be operated fairly reliably by personnel with little or no scientific background, an advantage deemed highly de-sirable in view of the nationwide network envisaged. Alternative techniques included the American high volume sampling system where physical and/or chemical analysis gives a measure of total suspended particulate. The British system, in contrast to this, only measures smoke (particle diameter 10 microns or under) and so care must be taken in international comparisons. Meetham (1964) estimated that about 85% of total suspended particulates in urban Britain consisted of smoke. If this is the case, a correction factor is possible although, given the changing nature of particulate emissions since 1964, this figure may no longer be applicable.

Errors inherent in the standard procedure were also outlined in British Standard No. 1747 Parts 2 and 3 (1969) relating principally to the smoke calibration curve used to relate the opacity of the filter paper and the concentration of smoke associated with it. The function used to derive this is itself the mean of many individual curves derived from individual observations at many different sites. A co-efficient of variation of 6% was obtained on the basis of 500 observations, giving a fair measure of overall accuracy since it is subject to all the 'normal' errors outlined below. A similar figure of 4% was obtained with the SO_2 measurement when concentrations exceeded 500 $\mu g/m^3$. With lower concentrations a wider error margin, $\pm$ 20 $\mu g/m^3$ was apparent. In an earlier study, five years previous to this, the Organisation for Economic Co-operation and Development (O.E.C.D., 1964) had reported an accuracy within $\pm$ 10% with concentrations over 100 $\mu g/m^3$, although this error inceased as concentrations fell below this value.

The Renfrew Air Pollution Project involved three such instruments situated at Linwood, Lochwinnoch and Erskine and their daily observations constituted the principal source of pollution data utilised in the present study. The practical experience gained in extracting this data and monitoring the performance of the equipment has led to several conclusions concerning the operational accuracy of the standard equipment and techniques under operating conditions.

It is initially apparent that the above estimates of accuracy assume that the instruments are in good working order, and that observations made from them are carefully and diligently performed. In practice this is not always the case. Air pollution monitors are characteristically sited in public or local authority run buildings and are maintained by non scientific staff. Routine readings are often hurriedly made, the requirements laid down are looked on as a tedious chore, and maintenance of the equipment may be minimal. In the absence of any feedback from Warren Spring Laboratory, equipment malfunction may occur undetected for lengthy periods with a consequent corruption of the observed data. Undoubtedly such problems are widespread and only the continuous supervision of data and equipment minimised their adverse effects at Linwood, Lochwinnoch and Erskine. However, several other sources of inaccuracy were continually being rectified during the six year period, which may be taken as symptomatic of problems affecting the accuracy of data from other sites in the National Survey. These can be roughly classified into electrical, mechanical and chemical in origin.

Failure of the public electricity supply, though infrequent has on some occasions disrupted results for periods ranging from one day to one month. This is particularly the case with monitors where the changeover from one bottle to the next day's is done automatically. Characteristically this more sophisticated instrument has eight days of bottles and switches from one to another at the appropriate time thereby reducing maintenance time considerably. However, power cuts, of even short duration, affect the timing mechanism of such 8 port valves, with adverse effects on perhaps the entire week's results. Electrical failure of the pump likewise can occur, particularly if ventilation is poor and overheating occurs. Leaks in the system, kinks in the tubing, malfunction of the gas meter are all faults which could be described as mechanical in origin. Those of a chemical nature, however, are less easy to identify and much harder to rectify.

The presence of ammonia in the air naturally results in some degree of neutralisation of SO_2, resulting in erroneously low readings. Martin and Barber (1971) found errors in 10% of cases for a sample study in the Midlands.

Most of the sites involved were located in rural surroundings reflecting the principal source of the gas from the decay of organic material. But while farmyards, abattoirs, cattlemarkets etc. are the most obvious sources, certain industrial and chemical processes are also considerable emitters. In this context ammonia emitted from the chemical and power plants on the Forth Estuary may exert minor influences on concentrations observed at Linwood with easterly winds though this is purely speculative without further research.

Martin and Barber also mention the possibility of obtaining spuriously low results due to unstable reagents. Over a period of days, sufficient carbon dioxide can be evolved from the hydrogen peroxide to raise its pH from 4.5 to 7 or 8, rendering it slightly alkaline. Equally serious is evaporation of water from the standard alkali or incorrectly made up N/250 sulphuric acid, used when the end point of the titration is overhot. In the Renfrew Project a specially accurate burette was used which enabled concentrations to be calculated more accurately than normal. The end point was measured to 0.01 of a millilitre using this instrument which also enabled fairly low sulphur dioxide concentrations to be measured accurately.

Other chemically related problems centre on the p.v.c. tubing. After two or three years these were found to be dark and sticky due to a photochemical reaction between SO_2 and the tubing. Although the losses entailed would be small, as pointed out by Martin and Barber (1971), replacement was carried out of all tubing at least once during the study period. Absorption by plants in the vicinity of the inlet is a further source of low readings although this factor seems to have been discounted for the instruments in Central Scotland, with the possible exception of Glasgow 44 (Comer, 1976). The intake of insects was, however, noted at Linwood and might affect results in a marginal way, though probably the problem was more frequent at a sewage treatment plant than elsewhere.

Changeover Times

A major element in comparability between sites relates to their changeover time. Prior to the introduction of automatic equipment it was stipulated (Warren Spring Laboratory, 1966) that changeover time should be as close as possible to midday, corresponding to a time of minimal pollution change and also to a convenient time for visiting the site. In practice, however, the guideline is seldom rigorously adhered to. (Comer 1976) notes that Motherwell, for example, operate on a midnight to midnight basis while Glasgow, like most other sites, have changeover times between 08.00 and 09.00 hours. Linwood and Erskine were also changed at this time. This is in some ways unfortunate since, at this time of day, the destruction of the nocturnal surface inversion is frequently being carried out by thermal and turbulent mixing corresponding to the time of day (Fig. 4.1), of most rapid change in concentration levels. Consequently, small time differences in changeover between sites can result in certain cases of partitioning a day's pollution in different ways. Monthly or seasonal averaging eliminates such fluctuations although daily correlation with meteorological features is rendered very difficult.

In addition to the standard monitors described above, reference was also made to a directionally sensitive monitor located at Linwood. This consisted of four equipments quadruplicating the daily equipment, one switched by an anemometer when winds were less than 5 knots, the others each covering 120^{o} sectors controlled electronically from a wind vane when winds were above that velocity. This enabled a check to be kept on the daily bottle as well as enabling pollution trajectories to be calculated.

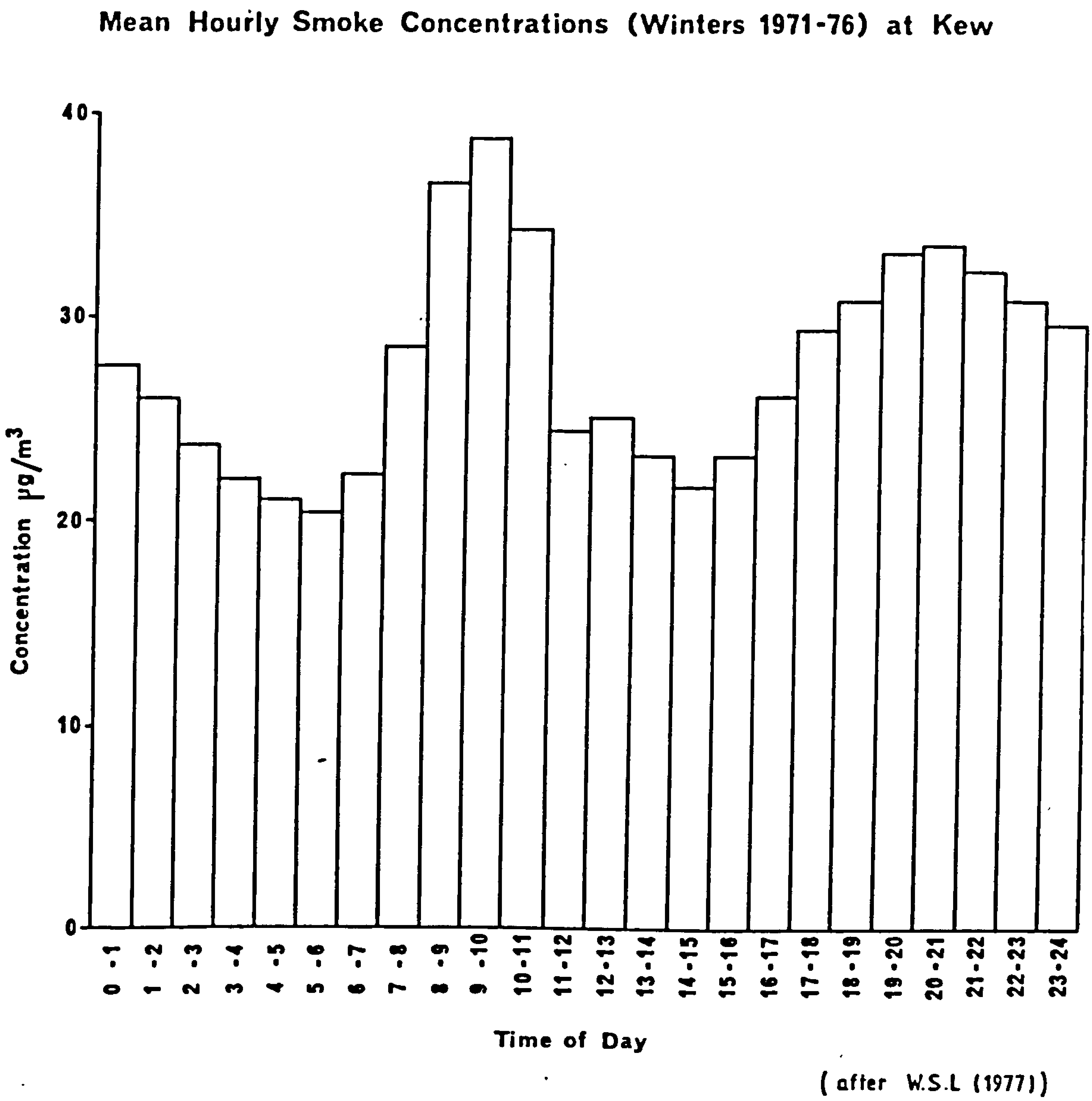


Fig. 4.1 Mean Hourly Smoke Concentrations (Winters 1971-6) at Kew

4.2 Meteorological Data

Published Surface Observations

The Daily Weather Report of the Meteorological Office publishes routine weather observations, transmitted every six hours to Bracknell, from about 53 locations in the British Isles. In addition to these first order meteorological stations, however, which form the basis for synoptic chart production and short term weather prediction, many times this number of auxiliary and other observing stations exist. These are mainly run by public bodies, amateur meteorologists and enthusiasts, and taken together provide a fairly comprehensive coverage of meteorological conditions in the British Isles. Perhaps the only major deficiency relates to conditions at the highest altitudes with no reliable routine observations since the closure of the manned observatory on Ben Nevis summit in 1904 (Farman, 1970). It is, however, to be hoped that this gap can at least in part be filled by the recent development of automatic weather stations located in high altitude areas (Curran et al, 1977).

A sample of data in coded form is published each day for the principal observing stations, one of which is Abbotsinch Airport, about four kilometres from the Linwood monitor. This station can be considered fairly representative of conditions in West Central Scotland, particularly if used in conjunction with data from Prestwick and Glasgow Weather Centre. With the latter, however, care must be taken since certain data, e.g. wind and nocturnal temperatures, are subject to urban influences.

A continuous plot of decoded data was made for Abbotsinch for the six year period from 1st June 1971 to 31st May 1977. Wind direction and velocity, visibility and cloud heights were plotted in conjunction with smoke and SO_2 concentrations at Linwood enabling simple conclusions concerning meteorological influences on pollution dispersal to be drawn. In particular the directional sensitivity of pollution, its inverse relationship to windspeed, and its enhancement on calm, cloudless nights were clearly seen. This record was subsequently extended for a further two years, giving an unbroken run of weather and pollution data from June 1971 to July 1979.

Upper Air Observations

Surface observations can be considered as providing one dimension or level of explanation of pollution meteorology. At least as important is data concerning conditions in the higher levels of the atmosphere into which emissions are increasingly injected. Conditions at the surface are strongly influenced by the thermal structure and the wind regime aloft and such factors as stability and the trapping of pollutants are explicable only on the basis of upper air data.

Twice daily radiosonde ascents are made at only three locations in Scotland : Lerwick, Stornoway and Shanwell, none of which is well located with respect to West Central Scotland. Shanwell (about 120 kilometres north east) and Long Kesh, Northern Ireland (about 170 kilometres southwest) are the most suitable sources of data for correlation with pollution data from the Clyde Basin and were thus the main sources of upper air information utilised. Following the precedents set by Halstead (1973) and Comer (1976) Shanwell was used when weather was coming from the east and Long Kesh data was used when a westerly or southwesterly circulation predominated.

Such an arrangement cannot be considered entirely satisfactory in view of the northeasterly situation of both stations, Shanwell in east Fife and Long Kesh in north eastern Ulster. The existence of a large land mass downwind of Long Kesh, and the North Sea downwind of Shanwell, subjects the air sampled at these points to modifications which may not be apparent, or may be more marked, in West Central Scotland. For example, in easterly winds, Shanwell exhibits a higher frequency of surface based and low level inversions, particularly in Spring, due to the effect of the air mass traversing the North Sea, than would be expected in the Clyde Valley.

Despite these drawbacks the temperature-height data was plotted twice daily to show the existence of inversions and any consequent limitation of the mixing height. Upper winds were also plotted enabling comparison with surface winds in terms of direction and velocity. This permitted examination of any wind shear with height, which might indicate the existence of an inversion layer. Partial thickness in the range 500-1000 mb was also plotted alongside the mean freezing level for each sample. The deviation between both plots indicated the intensity of subsidence or uplift and consequently gave a measure of stability, though this was not directly utilised in any analysis.

Considerable detail on atmospheric structure was also used from the European Weather Bulletin which was initiated during the study period and which published temperature-pressure graphs for various locations in Europe, including most of the British radiosonde stations. For most purposes, therefore upper air data was sufficient to enable regional scale temperature inversion occurrences and pollution episodes to be examined. Problems at the more local end of the scale persisted, however, and this, coupled with the inaccuracies of radiosondes during the first few hundred metres of their ascent, suggested the need for locally observed data concerning the lower levels of the atmosphere.

4.3 Other Sources of Data

Thermohygrograph Observations

The disadvantages of the two radiosonde stations were outlined above. Apart from not being completely representative of conditions in the Clyde Valley there were doubts as to accuracies in temperature measurement during the first few hundred feet. These disadvantages led to the development of a small recording network of thermohygrographs in an effort to provide continuous on site analysis of the local air mass at selected sites which would bridge the gap from the surface to the radiosonde. Three such instruments were deployed. The first, at Abbotsinch, located almost at sea level, was a continuous record of sea level temperature and humidity, while two further were located at Stanely Filters (grid ref. NS465610) and on the summit of the Gleniffer Braes at Sergeantlaw (grid ref. NS454598). These were exposed in a standard Stevenson screen, opening to the north east to minimise the chanqe of direct sunlight falling on the instruments. The thermohygrograph at Stanely was situated on a slightly convex slope and was enclosed on three sides, including the uphill one, by a wall 1.5 metres high. In part the location was chosen on security grounds, an important consideration as was later demonstrated at Gleniffer, but also such a wall minimised the oscillations due to cold air drainage off the surrounding hills, except where this phenomenon was on a scale sufficient to breach the wall. At Sergeantlaw the instruments were housed inside the perimeter fence of a military installation owned by the United States Navy for which permission and access were granted. Such a fence did not however prove a sufficient deterrent and subsequently damage to and loss of some of the instruments occurred at the end of May 1977 and necessitated premature cessation of the measurements. The apparatus was tended weekly and continuously checked for accuracy against maximum, minimum, wet and dry thermometers also located in the screens. This gave a record of temperature and humidity at altitudes of 2 metres, 100 metres and 250 metres respectively and enabled local inversions of temperature and some individual pollution episodes to be examined in detail.

<u>Infra Red Aerial Survey</u>

The area around the three monitors at Linwood, Erskine and Lochwinnoch was surveyed from the air in 1974 using Ektachrome Infra Red film which was designed to show any evidence of pollution damage to plant life in the area. This is due to the high reflectivity of living vegetation using this type of film. Although the mechanism causing this is not fully understood, it is probably associated with internal reflection within the leaf at cell boundaries and interstices (Sphere, 1974). Pollution damage attacks the leaf internally in the first instance and so on this type of film healthy vegetation appears as vivid red or magenta while affected leaves appear bluish green, much darker than their healthier counterparts.

Examination of the photographs under a stereoscope revealed no major signs of vegetation stress due to air pollution. More detailed analysis by the consultants responsible for the survey revealed a few isolated cases of vegetation stress.

(i) Some leaf damage was apparent in the area downwind of Glengarnock Steelworks. This was of a relatively minor nature.

(ii) Downwind from the Linwood monitor, and directly in line with the incinerator a line of dying oak trees might have been thought to be due to fall out from the incinerator, although age or drainage changes could equally be responsible. In the absence, however, of any other evidence of plant damage by this incinerator natural rather than man-made causes must be suspected.

Thus it would seem that little evidence of plant damage is apparent in this transect through the Lochwinnoch Gap. Detailed examination of the siting of the Erskine, Linwood and Lochwinnoch monitors thus suggests that, in a pollution context, they are reasonably representative of their surroundings and that their results can be considered fairly significant for a wider area. This was the main conclusion drawn from the survey in the absence of any evidence of definite vegetation damage caused by air pollution.

Other Sources of Data Considered

A variety of other data sources existed which time constraints prevented fuller development of. Principally these consisted of meteorological sources which were unavailable at the commencement of the project. The rapid development and introduction of acoustic radar is probably the best example. The obvious advantage which this apparatus has, of providing a virtually continuous record, is counterbalanced by many drawbacks the relative strengths of which are discussed in Chapter 12. Such an instrument was, however, deployed at Dalderse Sewage Works, near Grangemouth, during the course of the study period. This was done in conjunction with the Forth Valley Survey and comparisons were made between results obtained by radar and conventional radiosonde techniques. In particular the breaking up of the nocturnal inversion was particularly clear on the trace, as thermal plumes emanating from the surface increased in vigour until a near normal lapse was established. Such a trace however gave a qualitative rather than quantitative picture of atmospheric conditions and is relatively incompatible with numerical analysis techniques in its unporcessed state.

4.4 Computer Handling of Data

The volume of data entailed in the above proceedures was such that computerised handling of it became necessary at an early stage. In the first instance all data was punched on cards. This involved fourteen cards per day, or some 31,000 for the six year period. Such a volume of cards was itself unmanageable and disc storage was employed using the Northern Universities Multiple Access Computer, the I.B.M. 370/168 and I.B.M. 360/65. Eventually the data and programmes were archived on magnetic tape.

Several Fortran G level programmes were devised to analyse this data. Initially the emphasis was on listing the meteorological and pollution data. Secondly came the statistical analysis programmes which, in general, accessed the modified file ATMOSFILE. Finally came two suites of programmes concerned with the calculation of mixing height and inversion persistence. These latter programmes, by far the most complex, took several months to develop and accessed card, disk, and tape media in the one job step. These programmes are summarized below.

Pollut FA

This programme has as input the data from the Meteorological Office at Glasgow Airport. This consists of cloud amount, wind speed and direction, and a measure of visibility, all of which are in coded form. The programme decodes the data, produces secondary data useful in further analyses and prints out all of this in a readable form.

Pollut FB, FC

The input for this programme is that part of the upper air records from Shanwell and Long Kesh which consist of air temperature, pressure and dew point data. In this case the programme decodes the data and sorts it in order of decreasing pressure. It then inspects the sorted data to determine whether or not there are any inversions of temperature ; and if so, at what height (in terms of pressure) these inversions have occurred. In addition it determines, for each inversion, whether it is a true inversion or an isothermal, whether it has occurred at ground level or in the upper air, and whether it has characteristics akin to frontal or subsidence inversions. Finally, it prints this information in a readable form. Two forms exist, FB dealing with Shanwell data and FC dealing with Long Kesh data.

Pollut FD

This programme prints out the wind direction and speed at an altitude of 850 mb for Shanwell and Long Kesh at six hourly intervals and computes the daily average vector mean wind direction and speed at this altitude.

Pollmain FE

All the functions of the above four programmes are combined in this programme which is output, not in readable form, to the file ATMOSFILE, which the following programmes access.

Monthave

Reads smoke and SO_2 data (from ATMOSFILE) for any specified period and prints out the period specified, and the number of observations, sum of values, sum of squares, average, variance and standard deviation for both smoke and SO_2 for each month in the period. Months are indicated numerically 1 to 72.

Weehaver

Performs a similar function as Monthave with respect to days of the week.

Histocon

Reads smoke and SO_2 data for any specified period and prints out numerical histograms with variable class intervals.

Pollwind F1

This programme reads the surface vector-mean wind speed and direction (based on Abbotsinch Daily Weather Report Data) and smoke and SO_2 data (from Linwood) for any specified period ; and prints out, for smoke and SO_2 separately, a table of mean pollution levels for the given wind speeds and directions. Wind directions are grouped into 30^o sectors and windspeeds into 2 knot intervals. It also prints out the number of values in each cell of the table, the row and column averages and number of values, and the overall average and total number of values ; and the number of readings of zero wind speed (true calms) and the average pollution level for such values ; the number of readings of wind speed of 4 knots or less (relative calm) and the average, variance and standard deviation of pollution values for such readings. In addition it prints out the number of missing values of wind speed, wind direction, smoke and SO_2.

Pollwind F2

This is similar to the above programme in all respects except that as input it reads all four surface wind speed and direction readings from Abbotsinch, (instead of the vector mean of them). There are eleven possible variants of this programme handling any two, three or all four of these readings.

Stabwind

This programme reads atmospheric stability categories from the master file, and wind data for any specified period. It then prints out a table, for each stability category, giving the frequency of occurrence of each wind speed/direction combination. The categories correspond to a slightly modified version of Pasquill's categories and for each the print-out also gives frequency of true calms and the total number of observations excluding true calms.

(Stability categories were computed by Pollmain FE from the readings of wind speed and cloud cover (and time of day and year) taken daily at Abbotsinch).

Logmonav

This reads smoke and SO_2 for any specified period and prints out for each month considered the logarithms of the pollution values : number of observations, sum of values, sum of squares, average, variance and standard deviation.

Thermo JS

This programme analysed the thermohygrograph data collected at the three locations described earlier for the period from the 1st October 1975 to the 31st May 1977. As well as listing the data for each six hour period the strengths, locations and a measure of intensity of any inversions existing were also listed.

Mixht MH

This programme scanned all the available data sets for each twelve hour period. It identified and listed surface inversions where these occurred and then searched for free air inversions. Using formulae of proven accuracy it then calculated the heights at which these inversions occurred. This could be done with respect to base height, mid height or top of the inversion or isothermal layer. These were listed together with the occasions when no inversions were located. Variants of this programme selected which radiosonde station was most appropriate, or punched the output on cards, or directed to demountable disc storage where further use could be made of it.

Invsort AA

In addition to the functions of the previous programme this one ascribed each day's pollution to a particular set of inversion conditions. Smoke and sulphur dioxide concentrations observed when an inversion existed was alloted into 100 metre height bands. The mean concentrations with each height category of inversions was therefore calculated and displayed. The number of inversions occurring in each height range was also printed out. Variants of this programme considered nocturnal and daytime inversions of temperature separately and dealt with the Long Kesh and Shanwell ascents in various combinations depending on wind direction vectors.

Sicount SI

Surface inversions were examined in this short routine which classified them according to their time of occurrence and calculated the mean smoke and sulphur dioxide concentrations associated with each category.

Persistence IP

This was the most complex programme devised during the study. Designed to investigate inversion persistence it tracked inversion occurrences across temporal and altitudinal boundaries according to complex criteria outlined in Chapter 12. Inversion occurrences of various time lengths and whose mean altitude fell in various height bands were displayed. These individual inversion episodes were then aggregated to give information on persistence at various levels in the free air.

Once these programmes had been developed and tested successfully they provided an adequate data base for further analyses by the various package routines supported on the computer system mentioned. Foremost among these was the Statistical Package for the Social Sciences of which almost two hundred runs were made analysing various aspects of secondary data generated above. This extended to simple graphical output and correlation with elementary socio-economic variables.

In summary therefore the proceedure of collection, storage and analysis of data was as follows:-

(i) Pollution, weather and Aerological data was obtained from the monitoring stations and decoded from the Met. Office Daily Weather Reports and Daily Aerological Reports.

(ii) These data were transferred to coding sheets, punched into cards and stored on disc or tape as a master record.

(iii) Some programmes read only this file, printed out various aspects of it and computed secondary data.

(iv) The programme Pollmain FE transformed this master file to a new file ATMOSFILE containing considerable amounts of secondary data.

(v) Most of the remaining programmes, and the package programmes utilised read this file and output their results in print out form.

A schematic outline of this system can be seen in Fig. 4.2 which shows the various steps involved in the data analysis stage. It will be appreciated that the time involved in this section represented a considerable proportion of the time entailed by the whole project. At the end of the data analysis stage all of the programmes referred to, as well as the data sets involved, were archived on magnetic tape.

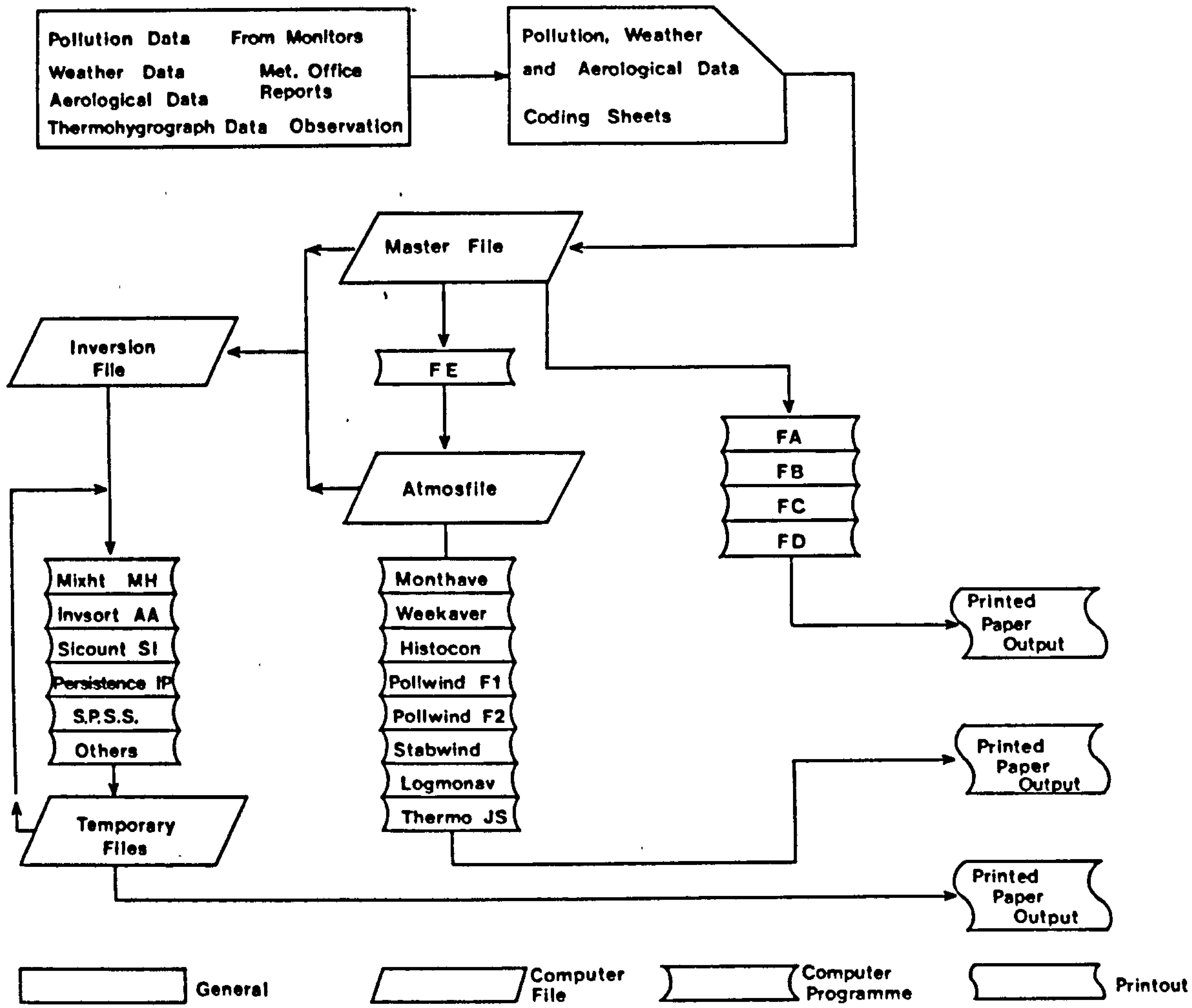


Fig. 4.2 Computerised Handling of Data Inputs

CHAPTER 5

POLLUTION CONCENTRATIONS - TEMPORAL CYCLES AND FREQUENCY DISTRIBUTION

5.1 Seasonal Fluctuations

Within the framework of the longer term trends noted in Chapter 3 there exists a series of shorter term cyclical variations in the observed concentrations, relating to seasonal and daily differences in the emission and dispersion environments. In terms of seasonal variations, then it is clear from Fig. 5.1 that mean monthly concentrations of both smoke and sulphur dioxide exhibit a distinct cycle with markedly higher values being observed during the winter months as compared with those of summer. This is particularly the case with smoke concentrations which fall from a monthly average of about 60 $\mu g/m^3$ in November to below 10 $\mu g/m^3$ in July. Such a marked diminution is due largely to the massive reduction in emissions related to domestic coal burning for space heating purposes which occurs during the summer months. This seasonal variation in the space heating component is observed throughout the energy market e.g. electricity demand in Central Scotland falls from a mid winter peak of 4,000 MW to a value less than 2,000 MW in summer (S.S.E.B., 1977). Though sulphur dioxide concentrations are also affected by this phenomenon, they are more a reflection of industrial activity, and for this reason they display a less marked seasonal cycle than smoke, falling from a maximum of 80 $\mu g/m^3$ in February to values around 40 $\mu g/m^3$ in mid summer.

The highest monthly smoke levels occur in late autumn and early winter and indeed November is the only month when average smoke concentrations exceed their SO_2 counterparts. This is almost certainly related to the temperature inversion conditions which characterise this time of year. In Chapter 12 it will be shown that low level persistent inversions are particularly frequent

MEAN MONTHLY CONCENTRATIONS AT LINWOOD

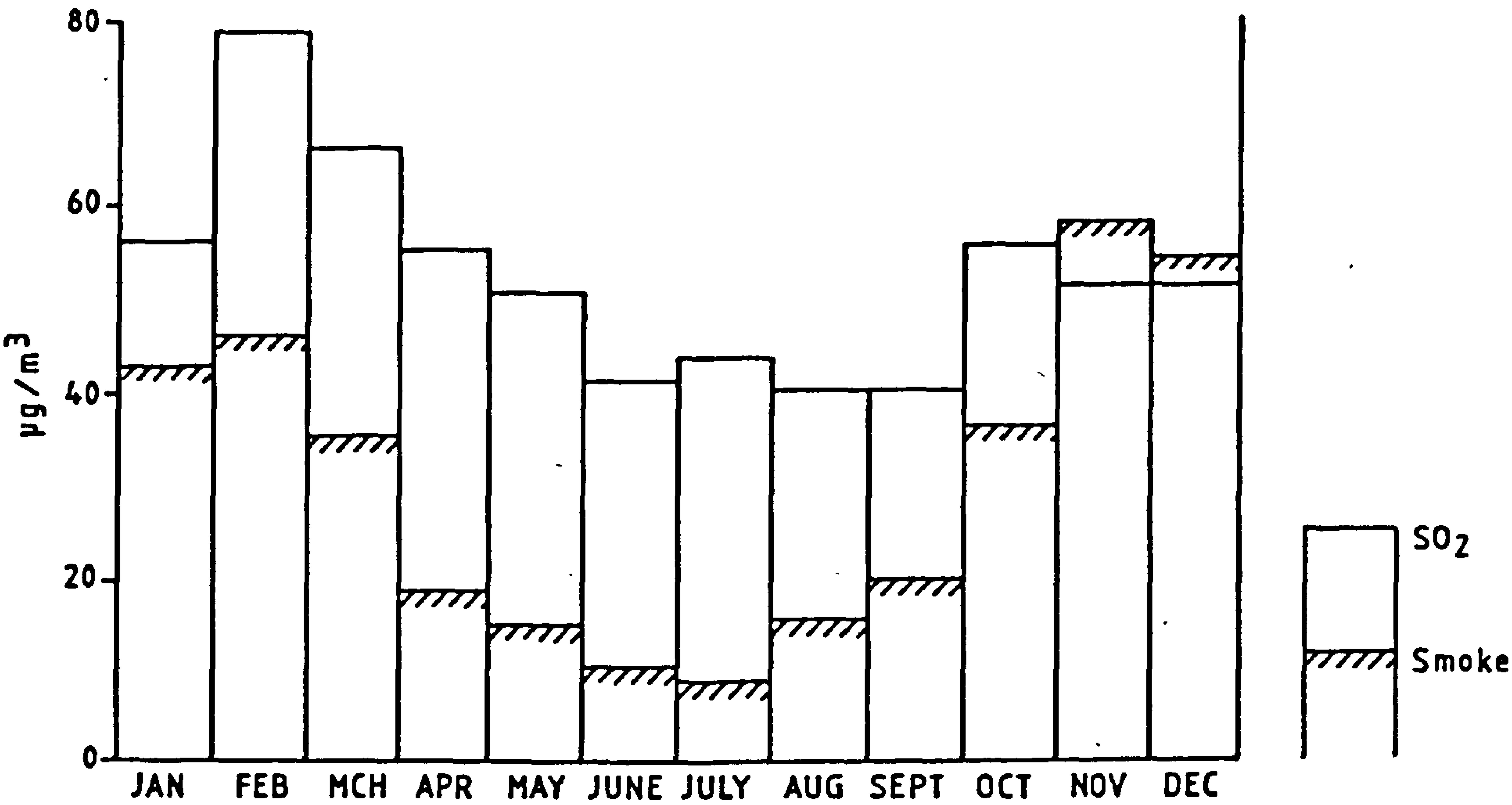


Fig. 5.1 Mean Monthly Concentrations at Linwood

during this period when land and sea temperature contrasts are slight and fairly stable conditions are common. The shallow, though rather weak, inversions which result are nevertheless capable of trapping less buoyant emissions, such as domestic smoke, thus producing the higher concentrations observed at this time of year.

Peak monthly values of SO_2 do not occur at the same time as smoke, but rather during the coldest winter month of February. At this time of year power station emissions are at their maximum. However, the inversion regime may also be very different during this month than during November for example. SO_2 plumes are more buoyant than smoke and would probably penetrate the shallow, rather weak inversions of late autumn. It may well be that these features are more intense in mid winter ; indeed this would be expected, and as such, peak SO_2 levels in February may also reflect this. It is unfortunate that little time was devoted to any examination of inversion magnitude in this study. Further research into this aspect might well have confirmed an increased incidence of intense inversions at this time of year.

Table 5.1 shows that considerable variations in the seasonal cycle are apparent when individual years are considered. This reflects the sensitivity of pollutant values to meteorological conditions. As far as smoke is concerned, winter was found to be the most polluted season for six of the eight years, autumn accounting for the remaining two. For SO_2 winter was the most polluted season for three occasions, spring for three, and summer on two occasions. For at least one of these summers during which values exceeded those of the following winter, mean temperature levels were higher than average, a greater frequency of warm summer weather was in evidence, and consequently a greater frequency of subsidence inversions may well have occurred. In part this would explain the higher than expected levels of SO_2 observed. Equally so, however, the occurrence

Table 5.1 Seasonal Averages 1971-1979 (Linwood 1)

Year	Summer		Autumn		Winter		Spring	
	Smoke	SO_2	Smoke	SO_2	Smoke	SO_2	Smoke	SO_2
1971-72	11	34	29	34	46	73	24	62
1972-73	10	47	39	64	58	80	27	36
1973-74	14	28	41	41	44	48	30	73
1974-75	10	22	37	40	35	52	19	54
1975-76	10	60	50	46	34	43	20	34
1976-77	10	60	29	57	63	85	16	95
1977-78	9	63	12	54	13	56	-	-
1978-79	-	-	21	28	51	66	13	36

of protracted spells of warm weather must be viewed as significant in terms of the conclusions concerning the increased incidence of photochemical pollution detailed in Chapter 14.

5.2 Weekly Pollution Cycles

The existence of a weekly pollution cycle was described by Bach (1972) with reference to observations from Sheffield. Both smoke and SO_2 average concentrations progressively increased during the working week, giving way to a sharp reduction at the weekend. Average smoke concentrations were some 30% and SO_2 some 10% higher on Fridays than their Sunday equivalents. He also noted that these trends matched almost exactly the weekly variation in the total number of fog days, thereby relating the provision of condensation nuclei from pollutant sources to fog frequency over a 20 year data run. Such conclusions would suggest that short term, local anthropogenic modification of weather due to air pollution is in evidence in addition to the long term global effects described in Chapter 2.

Using the programme Weekaver described in the previous Chapter the data was grouped and analysed on the basis of days of the week (Fig. 5.2). For both smoke and SO_2 a weekly cycle is clearly apparent. Both pollutants exhibit a maximum during the working week and a minimum on a Sunday. Smoke agrees better with the Sheffield results outlined above, with peak concentration occurring on Friday, some 29% higher than its Sunday equivalent. In this context it matches almost exactly the Sheffield case. However, a secondary maximum earlier in the week is also apparent. The reasons for this are not clear. It may be, however, that increased domestic smoke emissions on Tuesdays or Wednesdays reflect local circumstances e.g. early closing day for commercial premises etc.

Sulphur dioxide concentrations vary slightly more than for the Sheffield case, the values for the most polluted day being some 22%, higher than mean Sunday values. Peak values, however, occur not on the Friday but on the Tuesday. Again the explanation is not clear. Certainly data for Tuesdays include, due to the changeover time, all of the working hours on Monday and it may be that Tuesday includes extra emissions due to the need to heat premises or start machinery after the inactivity

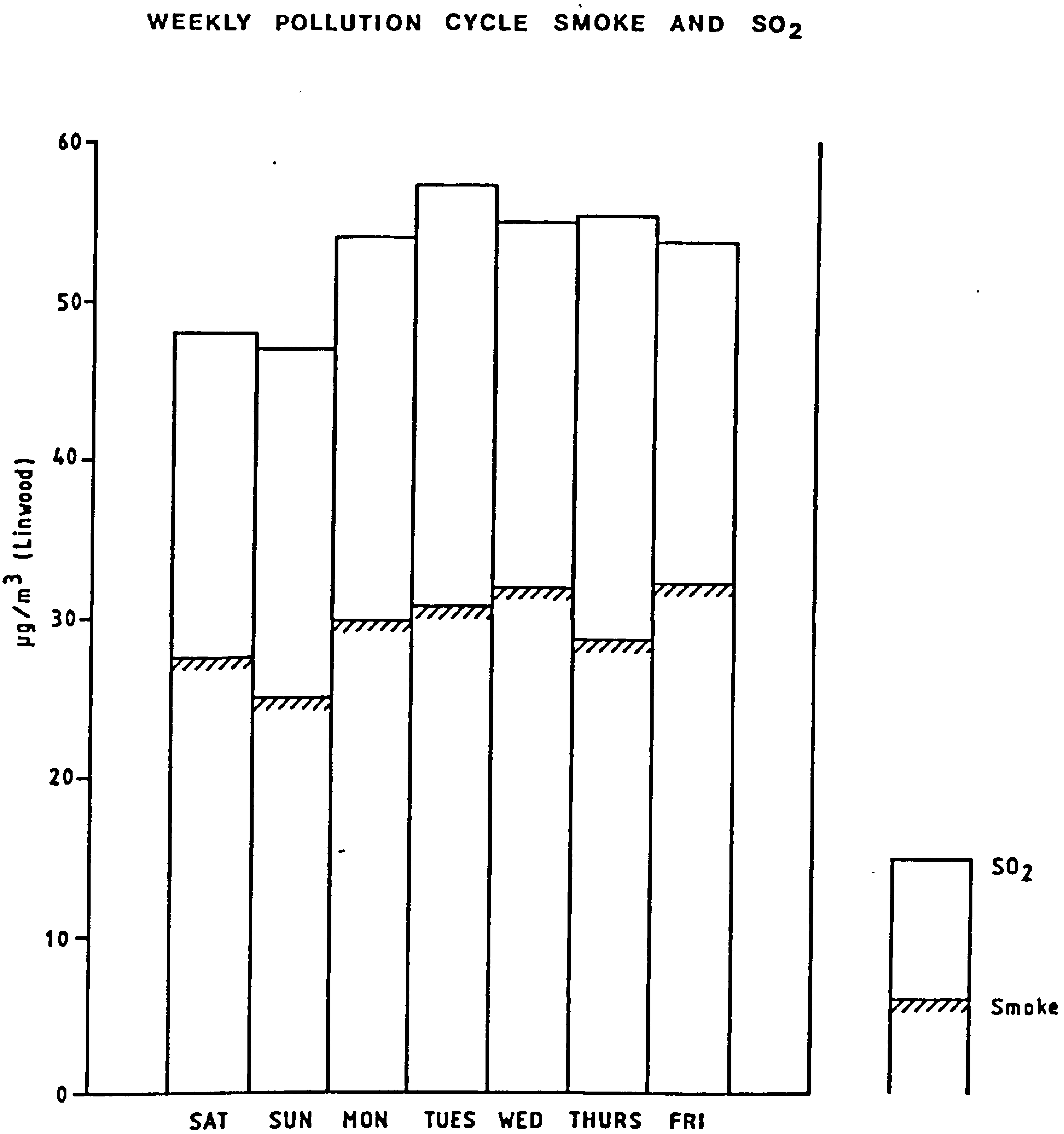


Fig. 5.2 Weekly Pollution Cycle Smoke and SO_2

of the weekend. Such a conclusion might also however apply to Sheffield. The changeover time is however not specified for the latter case and it may well be different from that at Linwood. It may be further suggested that ventilation is more vigorous and effective in dispersing SO_2 in Central Scotland and does not facilitate the accumulation of sulphur dioxide noted in Sheffield.

5.3 The Frequency Distribution of Pollution Data

The expected frequency distribution of daily values was obtained when a histogram based on 20 $\mu g/m^3$ class intervals was constructed (Figs. 5.3 and 5.4). It can be seen that both distributions are positively skewed towards low values, but with a very long tail towards high values. Calculation of the skewness index was done according to the formula :-

$$\text{skewness} = \frac{\dfrac{\Sigma\ (x - \bar{x})^3}{n}}{\left(\sqrt{\dfrac{\Sigma\ (x - \bar{x})^2}{n}}\right)^3}$$

With a normal curve this value is zero. A positive index is obtained if the peak frequency lies in the low value ranges, and vice versa for a negative value. Results showed that the degree of skewness was greater for smoke (3.64) than for SO_2 (2.40). Both values, however, demonstrate the fact that the data are not normally distributed, necessitating their transformation in order that the qualities of the normal frequency curve can still be utilized. Fig. 5.5 analyses the frequency distribution of daily SO_2 values, both for all wind sectors and for three selected sectors. In each case a perfect log-normal distribution would have produced a straight line on which all the points fell. Imperfections in such a relationship appear at very low and very high concentration values although despite this a best fit straight line has been drawn. On the basis of this it is possible to make estimates of the levels likely to be reached or exceeded over specified time periods. For example a value of 500 $\mu g/m^3$ can be expected on about one day in ten years, and one of 600 $\mu g/m^3$ on about one day in thirty years. In fact the observed extreme values do relate reasonably well to these predictions. Three values over 400 $\mu g/m^3$ occurred in the eight year period, one of which was between 500 and 600 $\mu g/m^3$. All occurred during winter

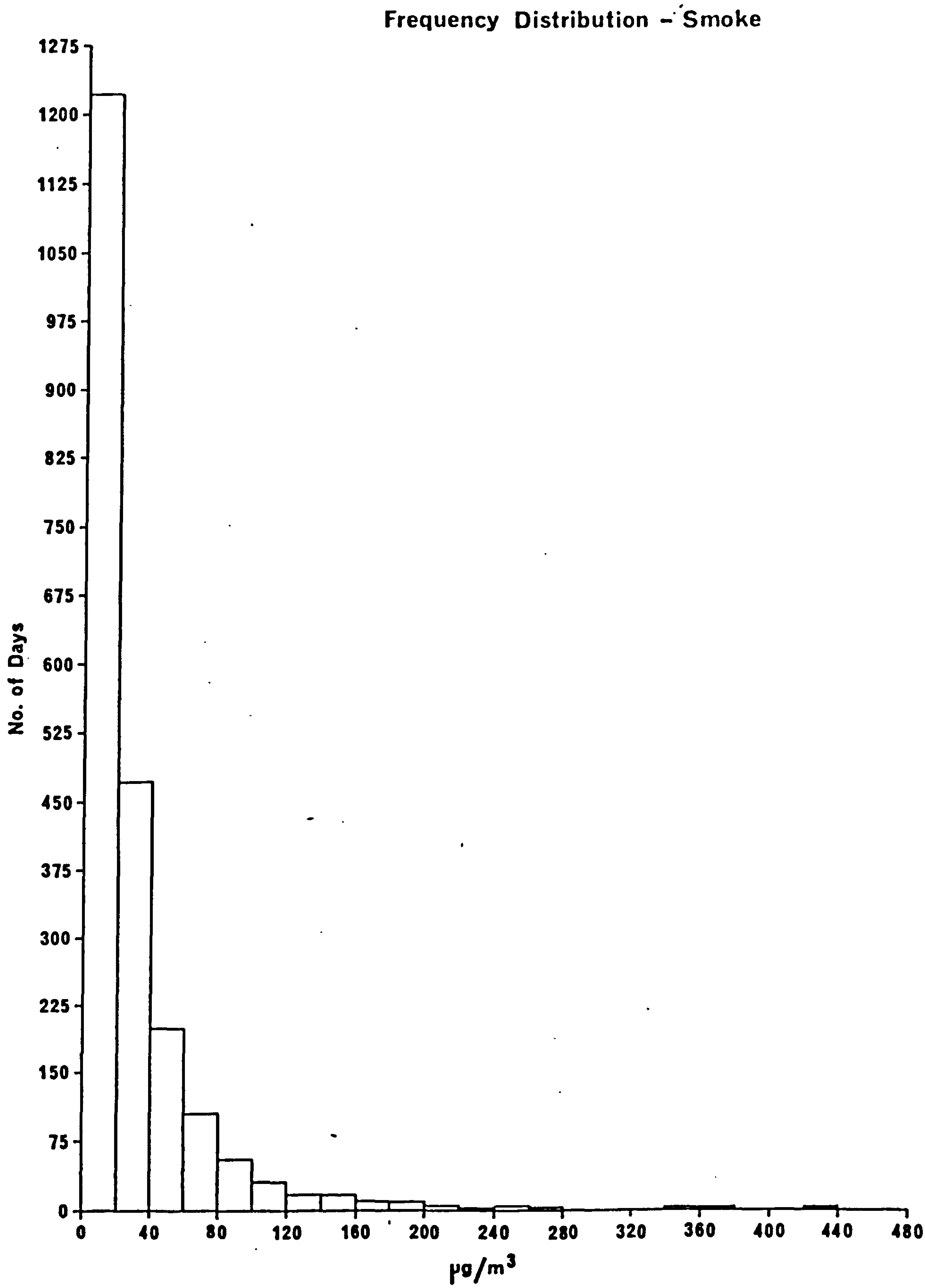


Fig. 5.3 Frequency Distribution - Smoke

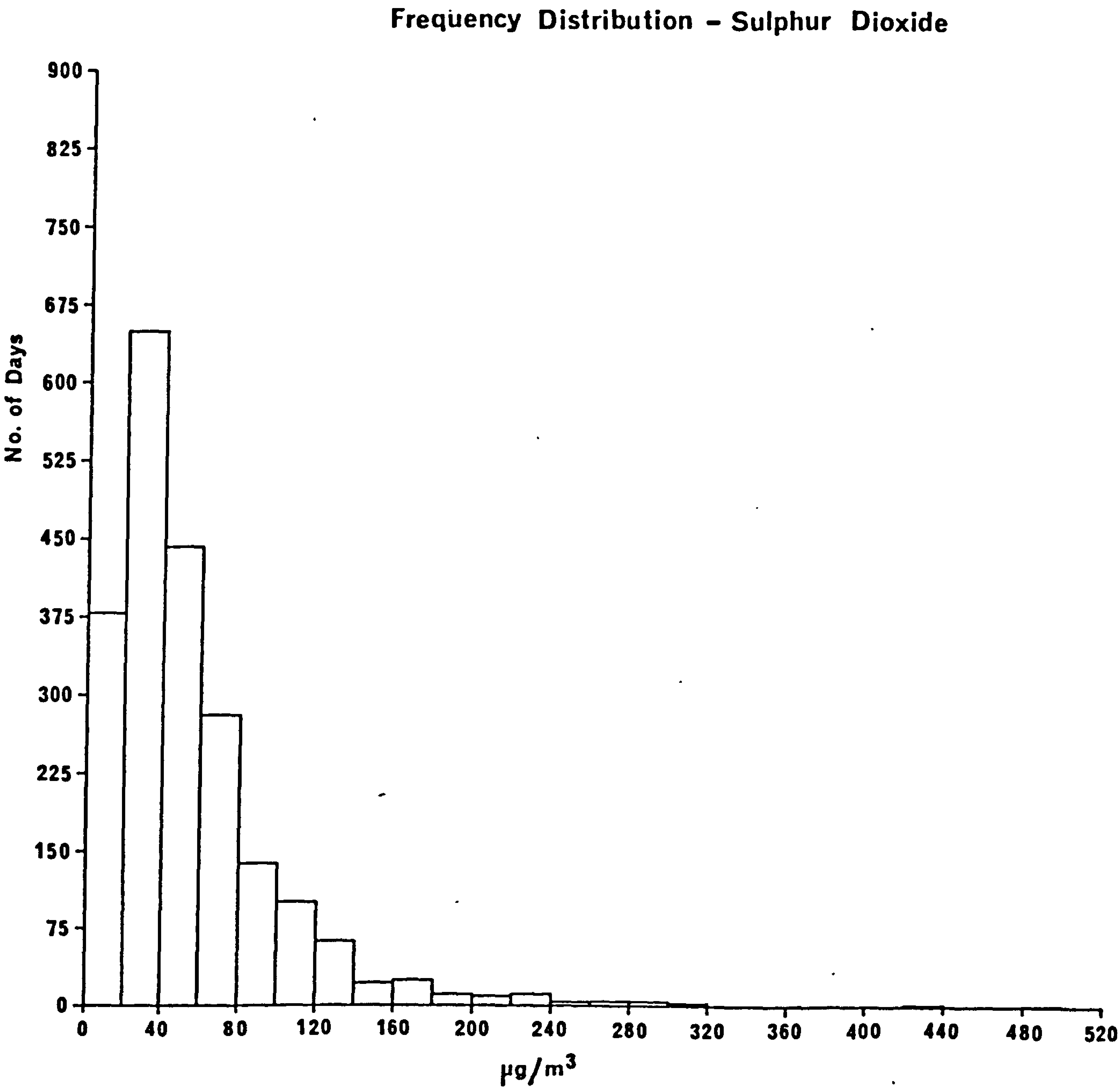


Fig. 5.4 Frequency Distribution - Sulphur Dioxide

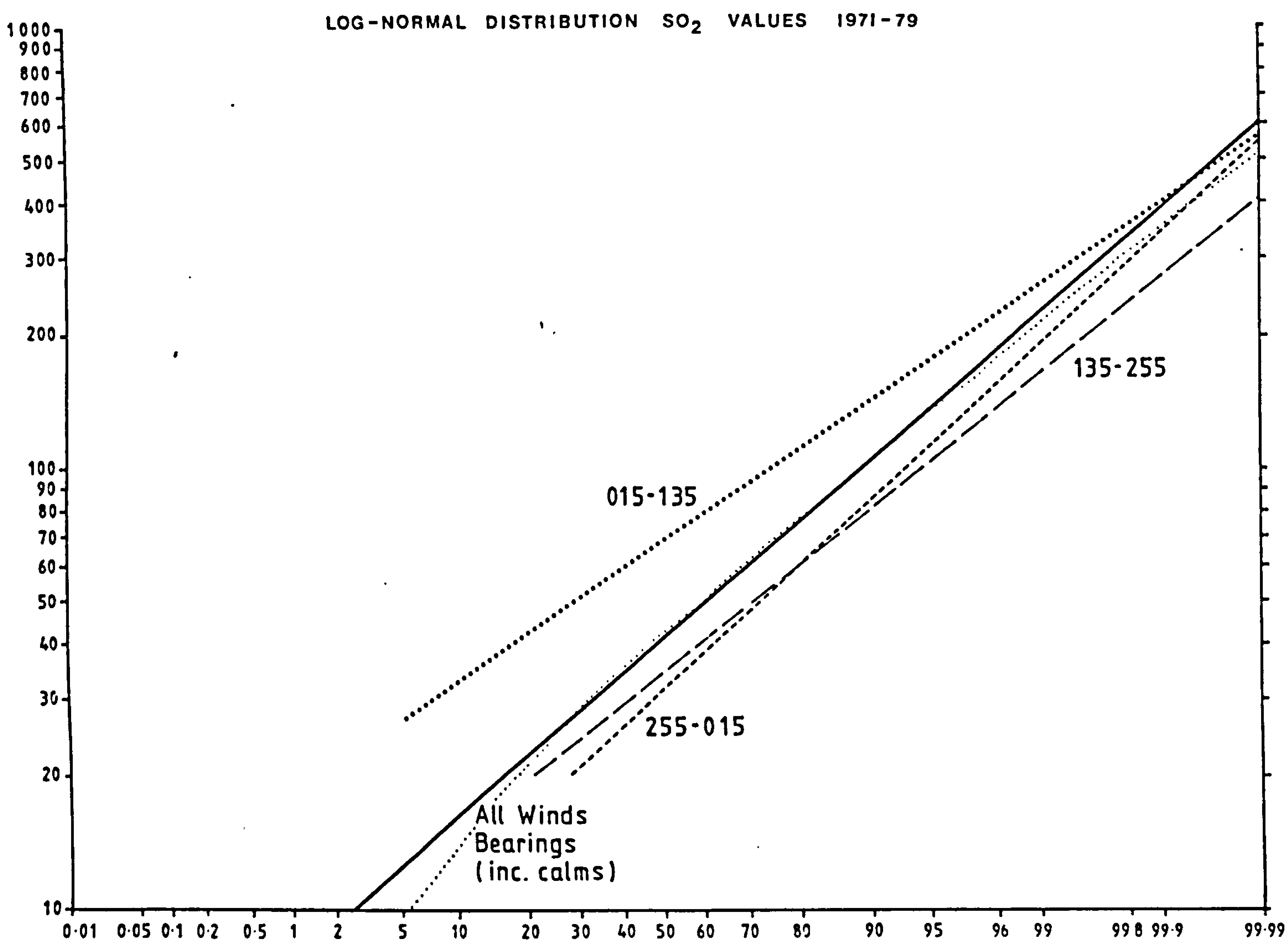


Fig. 5.5 Log Normal Distribution SO_2 Values 1971-79

fogs and are dealt with in detail in Chapter 13. Such a method of extreme value analysis cannot be relied on for absolute accuracy, however. Many of its conclusions are based on assumptions of a perfect log normal relationship. This is clearly not true, and departures from a single straight line clearly occur. Traces of a compound distribution exist, with the best fit line being something of a compromise between the distributions at lower values and those at higher ones. This may be related to changes in the sources, their strength or distribution or to changes through time (e.g. power station shut-downs), or even to different methods of dispersion related to changes in weather conditions.

Legrand (1974) has suggested that examination of such a log-normal graph can provide useful criteria for the classification of sites into such cateogories as urban, semi-urban, rural, industrial etc. This is done on the basis of the median and the slope of the plotted distribution. Such a method would seem to offer a more effective classificatory system than the rather arbitrary divisions at present utilised by Warren Spring Laboratory. Further investigations based on several sites might well confirm the utility of such a method.

Cyclical fluctuations on other time scales are dealt with elsewhere. Essentially, they relate to changing emission characteristics e.g. the economic cycle (Chapter 3) or to changing dispersion characteristics e.g. the daily cycle (Chapter 4). Considered together with the seasonal and weekly cycles discussed here and the longer term trends apparent in Chapter 2 the net product is of complexly interacting influences making each daily value a somewhat unique product and one which defies very accurate prediction regardless almost of how much information is available beforehand.

CHAPTER 6

THE ESTIMATION OF ATMOSPHERIC STABILITY FROM SURFACE OBSERVATIONS

6.1 Estimation Theory and Techniques

Climatology, in common with most branches of geography, has undergone considerable and fundamental changes in the past few decades. Even to summarize the nature of them would entail a considerable digression, but it is possible to isolate a common feature which they all share to some degree. At the root of most of the shifts in the research 'frontiers' has been a quest for model-based explanations. Yet while this quest has particularly characterised geography as a whole in recent times (Chorley and Haggett, 1969) it is by no means an entirely new phenomenon in climatology. Climatologists have always invoked models as means of conceptually representing meteorological phenomena. As early as the 18th Century Hadley (1735) was employing a model to explain aspects of the planetary wind circulation, a technique not dissimilar from that of Ferrel (1856), or scores of contemporary workers.

In each case the process of explanation was similar. Firstly an embryonic model was advanced, deficiencies in which led to its replacement by progressively more sophisticated versions incorporating further relationships and constituting more useful representations of reality. Such a process is apparent in air pollution climatology also and can be seen as the background to the progressive development of mathematical models used to predict ground level concentrations, in particular their generation of indices of atmospheric stability.

For a considerable length of time the theoretical estimation of ground level concentrations arising from specific emission sources was based on formulae developed by Sir Graham Sutton (1947). Increasingly, in the early 1960's the deficiencies in this model became apparent, in particular its assumption of a uniform topography, a steady wind, and, most importantly of all, the existence of neutral stability characteristics in the lower level of the atmosphere. The latter assumption made the extension of the model to conditions other than neutral fraught with uncertainties and dependent on empirical, often speculative, adjustment of the various diffusion parameters.

Among the first to attempt to quantify stability objectively were Kazanski and Monin (1960). They recognised that stability was basically a function of the surface sensible heat flux, H, and the surface drag τ. Using this criterion they evolved the following formula:

$$\mu = \frac{-g\, k^2\, H}{f\, C_p\, T\, \tau} \quad \text{i.e.} \quad \mu \propto \frac{H}{\tau}$$

where:

g = acceleration due to gravity, 9.81 ms^{-2}
k = von Karman's constant (taken as 0.4)
f = Coriolis Parameter, $1.12 \times 10^{-4}\ 5^{-1}$ (at 51^oN)
C_p = Specific heat of air at constant pressure, $1.012 \times 10^3\ J\ kg^{-1}\ k^{-1}$
T = Air Temperature, 290^ok

The problem of measuring stability this way obviously relates to the difficulty of measuring the surface sensible heat flux, and to a lesser extent the surface drag. For these reasons Kazanski and Monin's measure of stability never quite caught on. This was largely due to the alternative model proposed by Pasquill a year later (Pasquill, 1961).

Pasquill recognised that the two elements, sensible heat flux, and surface drag, could be represented by incoming solar radiation and the windspeed at 10 metres respectively. Using these two criteria he classified atmospheric stability into 5 categories A-E, ranging from very unstable through neutral to very stable. These classes remain the definitive measures of stability today (Table 6.1).

Table 6.1 Key to Pasquill Stability Categories

Wind Speed m/s	Isolatation			Night	
	Strong	Moderate	Slight	$\geqslant$ 4/8ths Cloud Cover	$\leqslant$ 3/8ths Cloud Cover
< 2	A	A/B	B	-	-
2-3	A/B	B	C	E	F
3-5	B	B/C	C	D	E
5-6	C	C/D	D	D	D
> 6	C	D	D	D	D

Source: Pasquill (1961)

Pasquill's categories were of interest to other bodies, other than those concerned with smoke or sulphur dioxide plumes. Notable among these was the nuclear power industry, anxious to be able to predict the detailed impact of unintentional discharges of radioactive material into the atmosphere. Their demands, therefore, were for an ability to classify stability on a short term basis, preferably utilising standard meteorological data only. The next modification to the Pasquill model not surprisingly came from research work associated with the Tennessee Valley Authority (Bruce Turner, 1964).

Turner retained Pasquill's method of classifying stability based on net incoming radiation and windspeed. However, he reasoned that, in the absence of cloud, insolation is a function of solar altitude, which in turn can be expressed in terms of time of day and time of year. This reasoning was then modified for existing conditions of cloud cover and cloud ceiling height. At night estimates of outgoing radiation were also made by considering cloud cover. Elaborate criteria were condensed into a form objective enough for use by computers, enabling 7 stability categories to be output, ranging from extremely unstable (1) to extremely stable (7). It was a version of this model which was used to derive stability classes in the present study.

The most recent reformulation of the model is probably that by Smith (1972) who converts Pasquill categories from a nominal (A,B,C, etc.) scale to an ordinal (1,2,3,....) scale. Intermediate values could exist, e.g. neutrality equals 3.6 etc. This has immense advantages when it comes to utilising stability data since it can now be manipulated and averaged in a manner hitherto not possible. But inevitably further refinements will appear as has been the case from Sutton's formulae onwards.

6.2 The Abbotsinch Stability Regime

A computer programme, based loosely on Turner's modifications, was utilised to examine the Abbotsinch cloud and wind data. Though originally designed as part of the Renfrew Air Pollution Project this programme was modified to enable it to analyse the six years of data involved in the present study. It should be stated that in its original form rigorous accuracy was not demanded, and the ouput therefore cannot be assumed to be a perfectly correct record of stability over the six years. Nevertheless it does given a fair representation of conditions even when compared with the formal Pasquill categories obtained by conventional means.

Stability parameters were calculated for every six hour period in the six years. A breakdown of the results according to 30^{o} wind direction sectors, and wind-speed in knots, can be seen in Tables 6.2 to 6.8. Category 1 corresponds to the most unstable, category 7 to the most stable conditions. Aggregate figures and percentage breakdowns can be seen in Table 11.1.

It is clear from the tables that extreme conditions of both stability and instability tend to occur with light winds (<6 knots) and calm conditions. Under such circumstances of minimal turbulent diffusion the radiation regime would obviously play the dominant role, promoting instability in conditions of strong insolation and vice versa. With stronger winds more neutral conditions are observed. This is apparent especially with south westerlies which seem to remain in the neutral category even with velocities over 20 knots. Indeed the overall figure of 48% of observations contained in the neutral category largely reflects the predominance of south westerlies and cloudy conditions. Easterlies and north easterlies are difficult to interpret, being represented well in both stable and unstable categories . Further comments on this anomaly are offered in Chapter 11 where it is suggested that it may in fact reflect air mass modification due to the heat island of Glasgow. Further analysis might well have confirmed this, in particular

Table 6.2 Wind Speed and Direction Frequencies for Stability Category 1 (Maximum Instability)

Wind Direction	Wind Speed (kts.)										
	1/2	3/4	5/6	7/8	9/10	11/12	13/14	15/16	17/18	19/20	20+
345-014	10	4	2	0	0	0	0	0	0	0	0
015-044	8	6	5	0	0	0	0	0	0	0	0
045-074	7	6	5	0	0	0	0	0	0	0	0
075-104	6	2	0	0	0	0	0	0	0	0	0
105-134	0	3	2	0	0	0	0	0	0	0	0
135-164	1	1	0	0	0	0	0	0	0	0	0
165-194	5	2	2	0	0	0	0	0	0	0	0
195-224	6	5	3	0	0	0	0	0	0	0	0
225-254	14	10	6	0	0	0	0	0	0	0	0
255-284	14	13	6	0	0	0	0	0	0	0	0
285-314	7	6	6	0	0	0	0	0	0	0	0
315-344	7	2	1	0	0	0	0	0	0	0	0

Number of True Calms = 129

Number of Observations (excluding true calms) = 183

Table 6.3 Wind Speed and Direction Frequencies for Stability Category 2

Wind Direction	Wind Speed (kts.)										
	1/2	3/4	5/6	7/8	9/10	11/12	13/14	15/16	17/18	19/20	20+
345-014	13	3	13	5	1	1	0	1	0	1	0
015-044	29	15	6	8	5	4	1	0	0	0	0
045-074	27	18	22	26	16	5	4	0	1	0	0
075-104	13	8	8	20	5	3	0	1	1	0	0
105-134	6	7	7	5	2	0	0	0	0	0	0
135-164	9	5	6	1	2	0	0	0	0	0	0
165-194	7	7	4	5	4	2	0	1	0	0	1
195-224	15	15	16	16	17	12	3	0	2	2	5
225-254	20	15	41	38	20	13	8	5	9	6	7
255-284	31	22	30	34	17	10	5	8	7	2	8
285-314	15	16	23	24	13	5	5	4	4	4	5
315-344	6	5	9	9	2	2	1	1	0	0	0

Number of True Calms = 186

Number of Observations (excluding true calms) = 977

Table 6.4 Wind Speed and Direction Frequencies for Stability Category 3

Wind Direction	Wind Speed (kts.)										
	1/2	3/4	5/6	7/8	9/10	11/12	13/14	15/16	17/18	19/20	20+
345-014	0	2	1	9	4	5	1	1	0	1	1
015-044	0	12	27	27	7	4	2	1	0	0	1
045-074	0	13	77	84	57	28	11	6	2	2	0
075-104	0	9	47	41	29	11	4	0	0	0	0
105-134	0	4	15	28	3	2	1	1	1	0	0
135-164	0	1	11	26	8	4	0	0	0	0	1
165-194	0	2	23	19	18	7	1	0	0	0	0
195-224	0	7	24	71	36	14	2	4	2	1	2
225-254	0	10	58	95	39	19	6	2	1	1	3
255-284	0	10	25	56	30	37	7	5	1	2	2
285-314	0	2	24	40	16	17	6	7	5	3	2
315-344	0	1	9	11	4	4	0	0	0	0	2

Number of True Calms = 0

Number of Observations (excluding true calms) = 1428

Table 6.5 Wind Speed and Direction Frequencies for Stability Category 4

Wind Direction	Wind Speed (kts.)										
	1/2	3/4	5/6	7/8	9/10	11/12	13/14	15/16	17/18	19/20	20+
345-014	0	0	0	2	8	11	5	4	2	1	0
015-044	0	0	0	18	21	18	13	6	4	6	2
045-074	0	0	0	120	123	123	74	45	31	16	6
075-104	0	0	0	76	76	77	32	15	7	1	0
105-134	0	0	0	32	34	27	16	9	4	1	3
135-164	0	0	0	29	33	27	20	21	10	1	4
165-194	0	0	0	27	49	55	38	45	36	11	22
195-224	0	0	0	58	111	126	117	102	64	61	114
225-254	0	0	0	98	111	154	130	100	85	56	86
255-284	0	0	0	43	62	82	83	79	41	29	57
285-314	0	0	0	12	27	35	25	26	17	10	14
315-344	0	0	0	8	8	6	9	4	4	1	0

Number of True Calms = 0

Number of Observations (excluding true calms) = 3752

Table 6.6 Wind Speed and Direction Frequencies for Stability Category 5

Wind Direction	Wind Speed (kts.)										
	1/2	3/4	5/6	7/8	9/10	11/12	13/14	15/16	17/18	19/20	20+
345-014	0	1	4	3	3	0	0	0	0	0	0
015-044	0	10	23	6	0	0	0	0	0	0	0
045-074	0	20	94	22	4	0	0	0	0	0	0
075-104	0	6	55	7	0	0	0	0	0	0	0
105-134	0	6	28	2	2	0	0	0	0	0	0
135-164	0	3	19	3	2	0	0	0	0	0	0
165-194	0	3	46	8	2	0	0	0	0	0	0
195-224	0	25	55	12	5	0	0	0	0	0	0
225-254	0	24	73	34	11	0	0	0	0	0	0
255-284	0	9	37	26	7	0	0	0	0	0	0
285-314	0	2	8	7	2	0	0	0	0	0	0
315-344	0	1	9	4	0	0	0	0	0	0	0

Number of True Calms = 0

Number of Observations (excluding true calms) = 733

Table 6.7 Wind Speed and Direction Frequencies for Stability Category 6

Wind Direction	Wind Speed (kts.)										
	1/2	3/4	5/6	7/8	9/10	11/12	13/14	15/16	17/18	19/20	20+
345-014	10	4	4	0	0	0	0	0	0	0	0
015-044	19	18	16	0	0	0	0	0	0	0	0
045-074	27	20	40	0	0	0	0	0	0	0	0
075-104	17	13	13	0	0	0	0	0	0	0	0
105-134	15	7	9	0	0	0	0	0	0	0	0
135-164	7	5	4	0	0	0	0	0	0	0	0
165-194	7	5	3	0	0	0	0	0	0	0	0
195-224	16	18	26	0	0	0	0	0	0	0	0
225-254	38	37	50	0	0	0	0	0	0	0	0
255-284	34	22	25	0	0	0	0	0	0	0	0
285-314	15	13	8	0	0	0	0	0	0	0	0
315-344	7	9	1	0	0	0	0	0	0	0	0

Number of True Calms = 341

Number of Observations (excluding true calms) = 582

Table 6.8 Wind Speed and Direction Frequencies for Stability Category 7 (Maximum Stability)

Wind Direction	Wind Speed (kts.)										
	1/2	3/4	5/6	7/8	9/10	11/12	13/14	15/16	17/18	19/20	20+
345-014	5	1	0	0	0	0	0	0	0	0	0
015-044	11	2	0	0	0	0	0	0	0	0	0
045-074	9	5	0	0	0	0	0	0	0	0	0
075-104	7	1	0	0	0	0	0	0	0	0	0
105-134	4	1	0	0	0	0	0	0	0	0	0
135-164	4	0	0	0	0	0	0	0	0	0	0
165-194	4	2	0	0	0	0	0	0	0	0	0
195-224	11	7	0	0	0	0	0	0	0	0	0
225-254	27	13	0	0	0	0	0	0	0	0	0
255-284	22	7	0	0	0	0	0	0	0	0	0
285-314	11	2	0	0	0	0	0	0	0	0	0
315-344	9	1	0	0	0	0	0	0	0	0	0

Number of True Calms = 200

Number of Observations (excluding true calms) = 166

the separation of data into daytime and night-time periods. This would provide scope for further investigation into Glasgow's 'thermal plume.'

In conclusion, therefore, it is apparent that markedly different dispersion conditions for aerial emissions are in evidence from the stability parameters calculated. Knowledge concerning the frequency of occurrence of such conditions is an essential pre-requisite for impact analysis regarding new sources and further reference will be made to them throughout this study. The most important element with which they must be considered, however, is wind, and it is to this attention now turns.

CHAPTER 7

WIND RELATIONSHIPS

7.1 The Abbotsinch Wind Regime

Dispersal of a pollution plume commences the instant it leaves the chimney and encounters the cooler surrounding air at the chimney top. Entrainment of this air in part reflects turbulence injected into the plume due to friction against the chimney sides. However, dispersal is mainly achieved through eddy circulation cells, caused originally by thermal or mechanical forces, which are superimposed on the average wind vector and are highly effective agents in diluting noxious emissions to more acceptable concentrations (Ledbetter, 1972). This was demonstrated by Halstead (1976) who estimated that a splay of only 1^{o} in the plume would dilute it with 1,000 times its own volume of ambient air after 1,000 m of rise. Plume dispersal formulae all rely heavily on wind data and it is clear therefore that the relationship between wind and pollution is of central importance in understanding meteorological controls on the behaviour of aerial effluent.

The meteorological station at Abbotsinch Airport is situated four kilometres to the east of the monitor at Linwood, about the same distance south of that at Erskine and some twelve kilometres north east of the Lochwinnoch monitor. It may be considered reasonably representative of conditions to the west of Glasgow and, in particular, of those influencing ground level concentrations of smoke and SO_2 at the above stations. A small selection of the meteorological observations made at Abbotsinch are published daily by the Meteorological Office in the Daily Weather Report. This includes the routine six hourly wind direction and velocity observations for the times 00h, 06h, 12h and 18h G.M.T. This information was decoded, extracted and plotted for each day during the six year period 1st June 1971 - 1st June 1977. The frequency of occurrence of each category was calculated and the directional results can be seen in Fig. 7.1 while those for velocity can be seen in Fig. 7.2 .

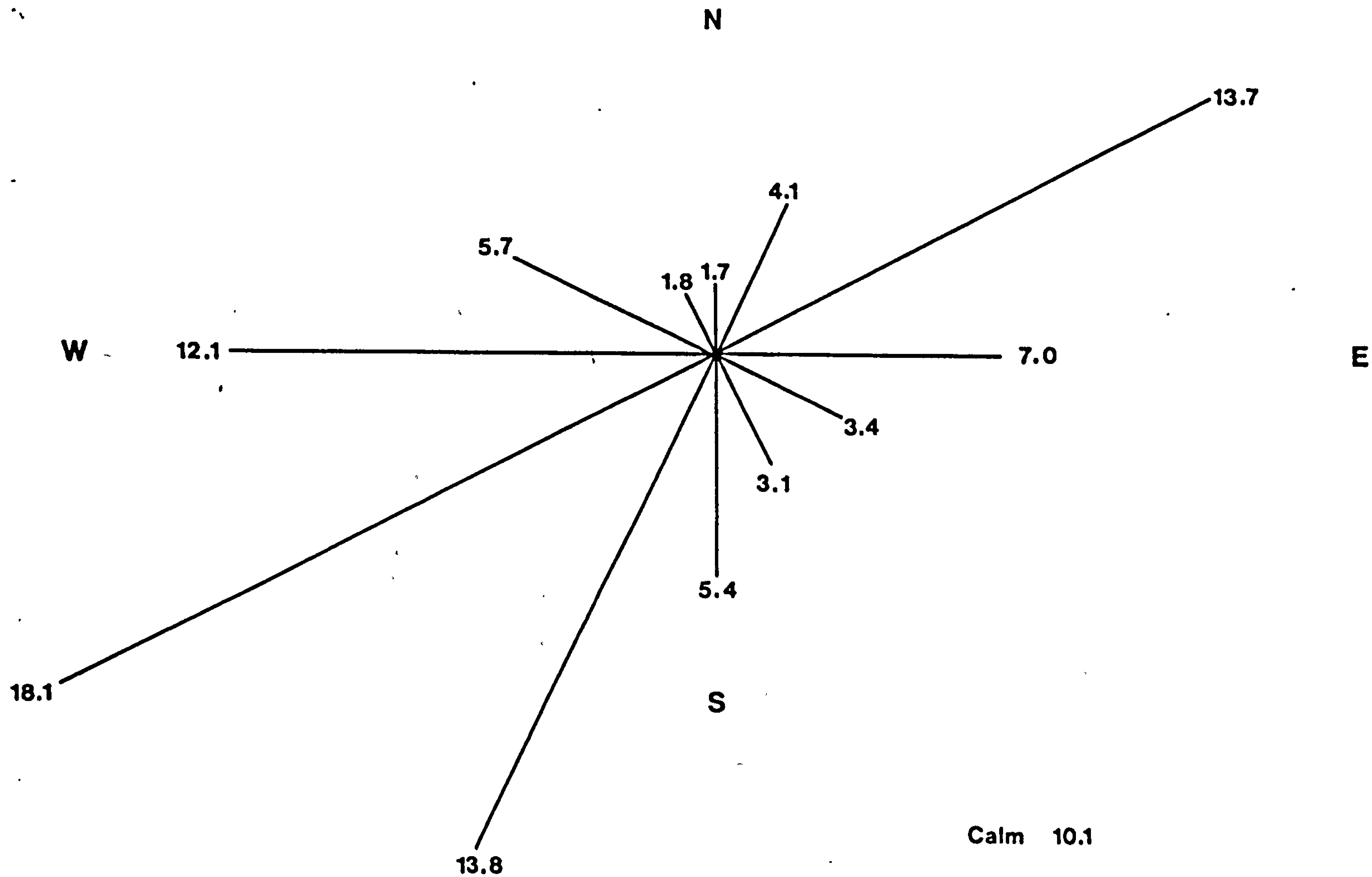


Fig. 7.1 Directional Frequency of Wind at Abbotsinch 1971-77

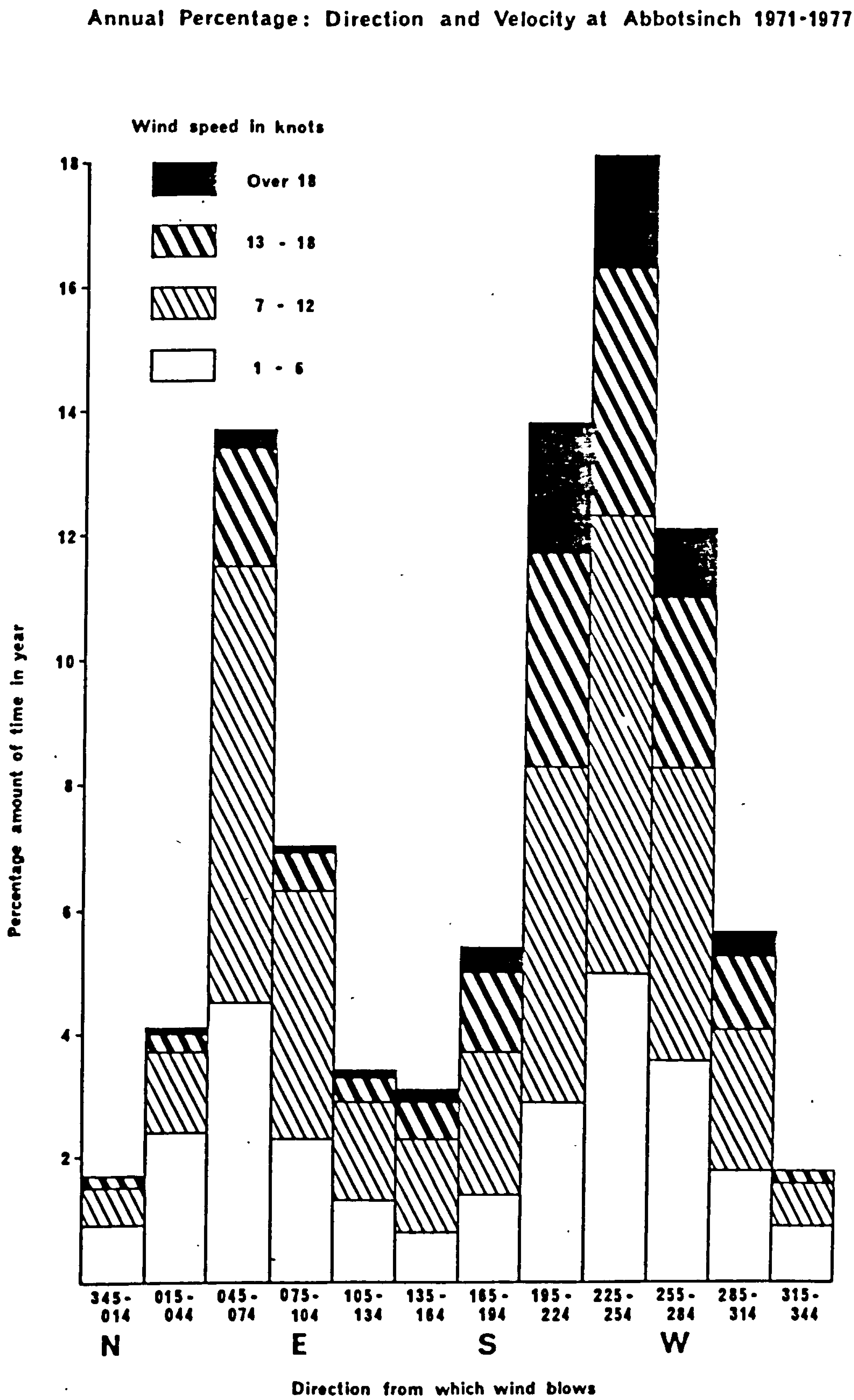


Fig. 7.2 Annual Percentage Direction and Velocity at Abbotsinch 1971-77

Table 7.1 Comparison Between Wind Direction Frequencies at Lerwick and Abbotsinch

Bearing (° true)	Lerwick	Abbotsinch	Difference
350°-010°	8.4	1.3	-7.1
020°-040°	6.0	2.6	-3.4
050°-070°	3.6	12.2	+ 8.6
080°-100°	3.1	9.1	+ 6.0
110°-130°	5.4	3.0	-2.4
140°-160°	9.4	2.6	-6.8
170°-190°	11.2	5.2	-6.0
200°-220°	8.6	10.1	+ 1.5
230°-250°	10.8	14.4	+ 3.6
260°-280°	9.0	13.6	+ 4.6
290°-310°	7.8	6.4	-1.4
320°-340°	8.6	1.4	-7.2
Calms (< 4 kts.)	8.1	18.1	+ 10.0
	(i)	(ii)	

(i) Lerwick Observatory 1950-1970
(ii) Abbotsinch Airport 1956-1965

The most frequent wind direction occurs in the category 225°-254°, a dominance which is also reflected at all but the highest wind speeds. These tend to occur in the adjacent category 195°-224°. This overall dominance of westerly and south westerly winds both in terms of directional frequency and in velocity terms is only to be expected and reflects on the synoptic situation most common to the area, the passage of Atlantic depressions along a south west to north east track between Scotland and Iceland.

A significant secondary maximum can be noted for the direction 045°-074°. In contrast to winds from a south westerly direction, the higher speed categories are poorly represented. The category appears to possess a predominance of lower wind speeds, a characteristic shared by adjacent categories. In fact the value of 11.5% of the total time during which winds below 12 knots blew from 045°-074° is only slightly lower than the corresponding value for 225°-254°. It would seem reasonable to conclude that these occasions of light easterly or north easterly winds relate to more settled anticyclonic type weather during which a light to moderate drift occurs across Central Scotland which is highly significant in terms of enhanced pollution. Frequently this transport of pollution occurs beneath the lid of a subsidence inversion, but this will be dealt with later.

By comparison with the south westerly and north easterly categories frequencies in other sectors are low. By comparison with observations elsewhere in Scotland, such as Lerwick, the wind rose is considerably distorted. Table 7.1 shows the Abbotsinch and Lerwick data in conjunction. The percentage reduction or enhancement of the Abbotsinch data is also tabulated. Clearly relief considerations on a large scale are important. The shelter provided by the Highlands and to a lesser extent by the Southern Uplands and even England can be noted from the Abbotsinch data. For example, for only 2.7% of the time are winds in the 60° sector 315°-015° observed. Perhaps even south westerly frequencies are slightly suppressed by the effect of Ireland providing at least a modicum of shelter in this direction.

Detailed theoretical prediction of wind conditions for projected industrial sites is impossible due to the great variety of possible conditions. It is feasible, however, to make some allowances for different exposures and locations. From this an estimated wind rose for the particular site could be derived from Abbotsinch data and a more detailed impact statement would be feasible. Though this has not been attempted in this study it is an example of where future research could be useful in relation to possible Public Enquiries into the pollution aspects of projected industrial development.

The frequencies computed for Abbotsinch compare well with those based on ten years of hourly averages which Plant (1967) utilised from nearby Renfrew Airport for the period 1956-1965. This would tend to suggest that the six year study period was not excessively atypical or anomalous in terms of its circulation characteristics and by implication its overall climatic conditions.

7.2 Wind Direction

Considerable fluctuation in wind direction may occur during the course of a day. This is a consequence of the rapid synoptic changes which characterise the climate of the British Isles and so distinguish it from more continental regimes (Manley, 1952). This means, however, that daily concentrations of smoke or sulphur dioxide often reflect a compromise between widely contrasting conditions. For part of the day the air sampled by the monitor may have been blown across open moorland or mountainous areas, encountering little or no air pollution, while for the remainder of the time it may have traversed industrial areas and become heavily laden with particulate and gaseous emissions. This can be demonstrated by reference to the behaviour of the Glasgow pollution plume over a six day period from the 9th to 15th November, 1975. For the first half of the period it crossed the Linwood area from east to west in association with an easterly anticyclonic drift, while for the second half of the period the same air mass returned from west to east as the wind swung round to the west with the approach of a warm front. Such a phenomenon was observed on more than one occasion during the six years and serves to emphasise the pitfalls which can occur in the interpretation of directional data.

In an effort to obtain some measure of wind direction which could be correlated with observed concentrations the average vector mean wind was calculated for each day. This was the resultant value obtained from the resolution of the four component observations made at six hourly intervals each day. Such a method has a smoothing effect on the data and produces a slightly more subdued pollution wind rose than would using all four observations individually. This can be seen in Fig. 7.3 which shows the relationship between these two measures of wind direction and the smoke and sulphur dioxide associated with each 30^{o} category for Linwood for the period 1971-1977.

Smoke and SO_2 Concentrations by Wind Sector (Daily Vector Mean Wind)

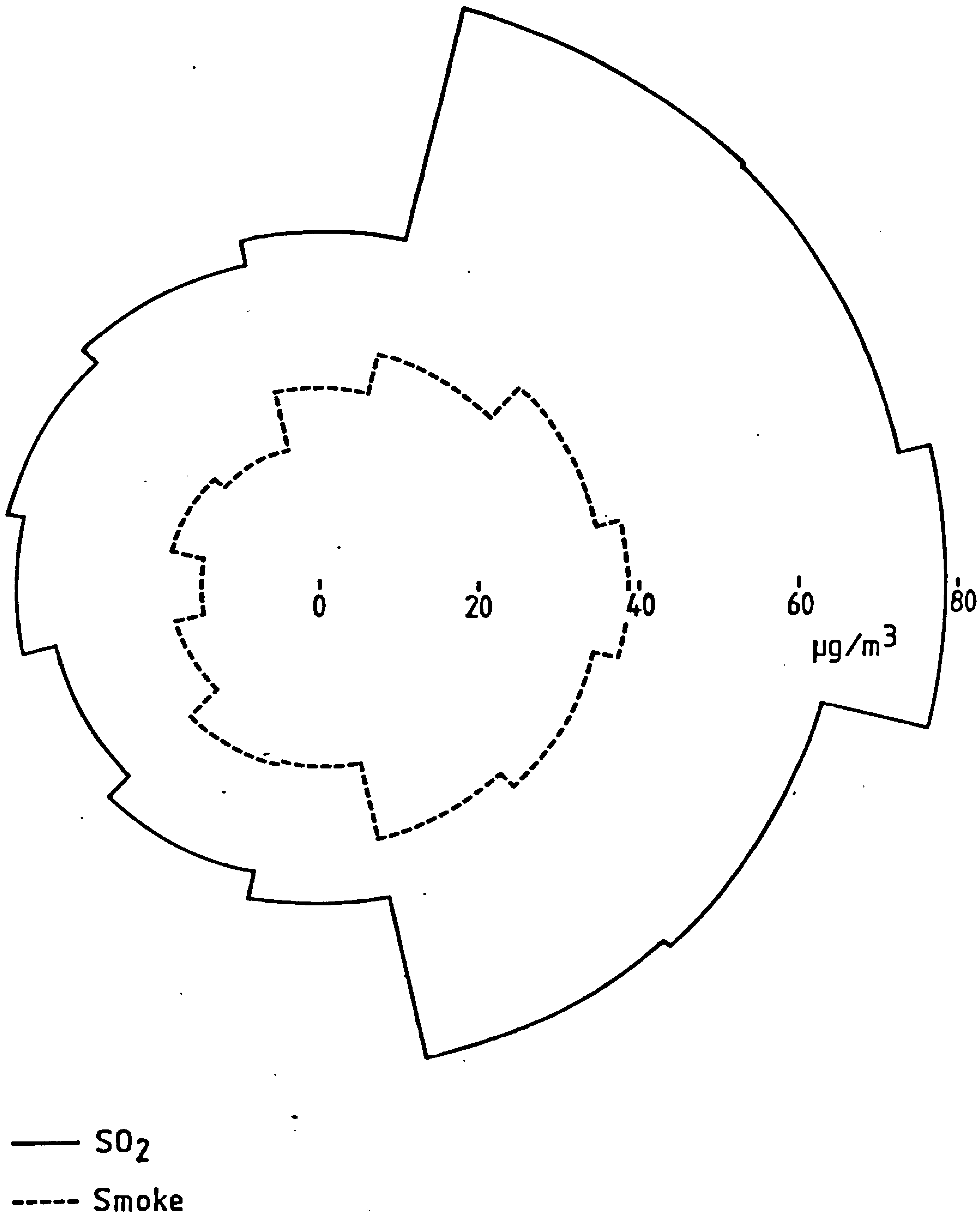


Fig. 7.3 Smoke and SO_2 Concentrations by Wind Sector (Daily Vector Mean Wind)

In terms of smoke pollution it is at once apparent that concentrations are highest with easterly winds and lowest with northwesterly wind bearings. Average values between 30 and 40 $\mu g/m^3$ occur in the sector 015^o-164^o in contrast to values of about half of these for other wind sectors. Such a contrast is to be expected in view of the proximity of much of the Clydeside conurbation. Air coming from a variety of directions in the eastern and southern quadrants will inevitably transport pollutants from industrial, commercial and domestic sources both from the Glasgow Area and also conceivably from more distant sources beyond the city. Nevertheless, concentrations are relatively low despite this, some explantion for which would seem to lie in the effects of smoke control. As was outlined in Chapter Three considerable parts of Glasgow and its major outliers are now under smoke control orders. Yet while domestic coal burning was found to account for up to 99% of smoke pollution in parts of the Forth Valley (Warren Spring Laboratory, 1976) it would be wrong to attribute a similar figure to areas to the west of Glasgow. The transport of the Glasgow smoke haze under easterly winds can be easily observed from any of the overlooking lava plateaux and this tends to confirm that industrial smoke is an important component in the Linwood observations. Glasgow smoke has been observed as a contributory factor in reducing visibility as far west as Islay (Halstead, 1958).

The lowest smoke values are seen to occur on westerly and north westerly winds corresponding to the line of least population density. Relatively few industrial or domestic emissions are found in this direction and background values for clean air of 15 $\mu g/m^3$ (below 10 $\mu g/m^3$ in summer) may be assumed. Also located in this direction, however, is a recently constructed municipal incinerator and it might be thought that some effect would be detected at the monitor which is sited about 100m away. This has not been the case. Examination of smoke concentrations over a wide range of meteorological conditions have failed to produce any noticeable effects from this source. It would thus appear that the plume passes overhead and no significant downwash seems to occur.

Table 7.2 Power Stations Order of Merit on Fuel Cost Basis - Effective Summer 1976

Order of Merit	Station	Set. Nos.	Capacity MW	Fuel Cost £per MWh.
1	Hunterston 'B'	7	459	1.99
2	Methil	1,2	57	2.09
3	Hunterston 'A'	1-6	300	2.40
4	Barony	1,2	42	4.84
5	Longannet	1-4	2304	7.73
6	Cockenzie	1-4	1152	9.06
7	Kincardine	4,5	375	10.07
8	Dundee 'B'	1,2	230	10.90
9	Kincardine	1-3	339	11.07
10	Braehead	5	56	13.59
11	Dalmarnock	1	57	13.69
12	Braehead	3,4	99	14.25
13	Dalmarnock	8.9	75	14.75
14	Dalmarnock	2	50	14.77
15	Dundee	7	23	15.36
16	Braehead	1,2	79	16.17
17	Portobello	1-3	140	16.34
18	Clyde's Mill	9-12	90	16.40
19	Dundee	6	23	17.43
20	Clyde's Mill	13	55	24.75
21	Dunfermline	2,3	140	28.08
22	Dundee	5	15	28.65

Source : S.S.E.B. (1977)

Sulphur dioxide values mirror to a large extent those of smoke on the directional plot. The 30° sector 75°-104° is again the most polluted on the vector mean wind plot although the adjacent sector 45°-74° is equally significant on the four winds plot (See Table 7.4). This suggests that the principal source area is located on a bearing between 040° and 055°. If such a sector is drawn on a map of the area it encompasses Braehead Power Station on the banks of the Clyde near Shieldhall.

Braehead, together with Dalmarnock and Clydes Mill power stations constitute an older generation of power stations, originally coal-fired, which are located within the built-up area of the conurbation. The chimney tops of all are located below the 100m contour which almost encloses the basin, and all fall within the 015°-165° sector which accounts for the majority of cases when the mean level of 51 $\mu g/m^3$ was exceeded. A fourth power station, at Yoker, was also operative for part of the period. During the sixties and early seventies the introduction of new generating capacity both on the Clyde and Forth Estuaries rendered these older power stations obsolete and expensive to run. A policy of selective phasing out was therefore applied resulting in the closure of Yoker and Clydes Mill. Braehead and Dalmarnock continued to fulfil a somewhat reduced role for much of the study period, coming on during times of high electricity demand or when technical or industrial problems affected the larger stations, particularly Longannet and Hunterston B. In their efforts to produce energy as cheaply as possible the South of Scotland Electricity Board operated a league table of operational efficiency with least cost stations utilised on a more regular basis than those which were less efficient. A copy of this table for May 1976 can be seen in Table 7.2. It will be seen that the three stations at Braehead, Dalmarnock and Clydes Mill fall well down the order of merit list. This is despite the conversion of the first two to oil-fired boilers. The operating cost of Clydes Mill, for example, is almost twelve times that of the most efficient stations. The order in which these stations were phased out of production is therefore this order of merit table in reverse. Clydes Mill was closed between 1976 and 1977 while Dalmarnock was closed on 31st March 1978. At the same time Braehead was relegated to a considerably reduced role in power generation.

These are highly significant developments from the point of view of sulphur dioxide concentrations. The closures described above are intimately linked to the installation of new capacity at Inverkip to the west of the monitors, which will be dealt with more fully in Chapter 15. The significance of a changing power station emission pattern and the replacement of three or four low level medium intensity sources by one high level, high intensity source downwind of the prevailing wind should not be underestimated, however.

For the appropriate sector corresponding to Braehead, mean SO_2 concentrations in 1971/72 were of the order of 84 $\mu g/m^3$. The corresponding value for 1972/1977 was 77 $\mu g/m^3$. Such a diminution is commensurate with the reduction in operations mentioned above and reflects the station's use as a peak load booster. However, insofar as the cold spells in winter when peak electricity demand occurs correspond to easterlies then Braehead exacerbates the basin's susceptibility to air pollution episodes. This was already noticed in Chapter 5 on the frequency distribution for Linwood SO_2 and the intermittent operation of Braehead may be partly responsible for producing the long tail of high pollution values described there.

As well as encompassing Braehead Power Station the sector of maximum pollution also includes the Longannet, Kincardine and Grangemouth complex of major high level sources. There is evidence in the data that under certain meteorological circumstances pollution from these more distant sources is detected at Linwood. Longannet in particular, the Scottish base load power station accounting for 50.2% of all the electricity generated by the S.S.E.B. in 1976/77, probably contributes considerably to this sector's pollution. The circumstances under which this occurs frequently involves inversion trapping and will therefore be dealt with in Chapter 11.

No other marked directional maxima are apparent. There is, however, a slight maxima corresponding to the direction of Dumbarton and the Vale of Leven which is apparent on the 'four winds' plot but not on the vector mean wind rose. This occurs at 315^{o}-344^{o}. Its significance appears to have reduced over the study period and this would tend to refute the suggestion that it is the increased industrial and residential activity in the Vale of Leven which is responsible. A more plausible explanation lies in attributing the pollution to the Royal Ordnance Factory at Bishopton, now declining in importance somewhat. Such an installation of course does not fall within the range of the Clean Air Acts.

Graedel (1977) treated directional data divided into 30^{o} sectors after a boxplot technique originally suggested by Tukey (1970). This involved analysing each directional distribution separately to yield its median, upper and lower quartiles, and the range of values involved. From this several deductions concerning the nature and intensity of sources could be made. Though not designed for use with large area sources the analysis was applied to the Linwood data. The variance of each 30^{o} sector was analysed separately and the results can be seen in Fig. 7.4.

Extreme values are seen as most likely with winds from the north east and east. Again these are circumstances when inversion trapping at quite low levels might occur and when most of the sources mentioned earlier to the east of the monitors would be contributing to daily concentrations. The progression of the medians in fact shows a matching trend to the mean values already described. This is only to be expected. What does appear striking however, and which earlier analysis has not brought out, is the differing interquartile ranges which are apparent for the various directions.

Two distinct families of distributions can be identified. Firstly the directions 345^{o}-134^{o}, stand out as being higher than average in terms of their concentrations, charactertised by relatively large inter quartile differences, over 50 $\mu g/m^3$,

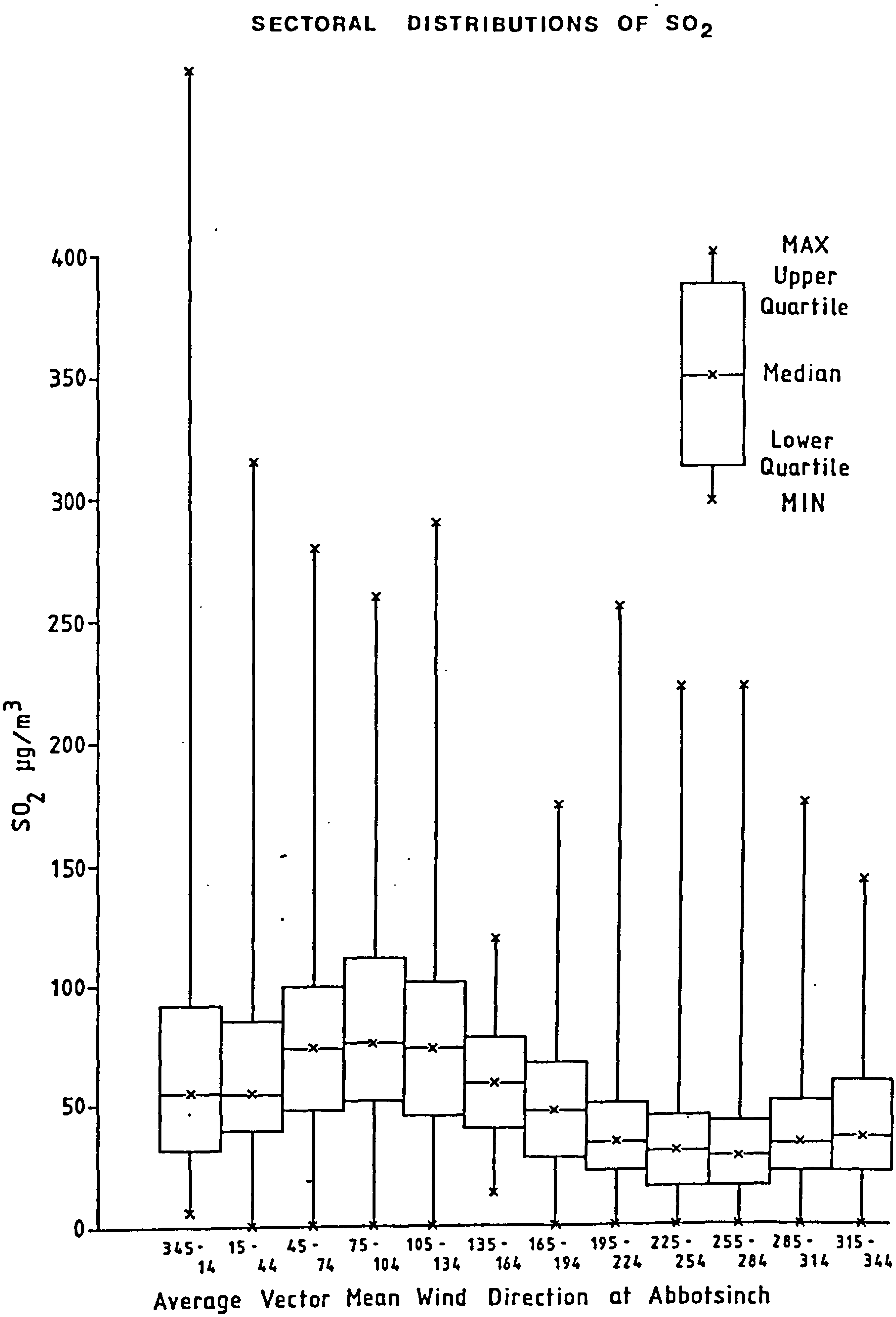


Fig. 7.4 Sectoral Distribution of SO_2

and with long 'tails' indicating a susceptibility for high pollution values. On the other hand, the directions $135^{o}-344^{o}$ seem to be more discrete distributions. Medians are, with one exception, below overall average concentrations, inter quartile differences are between 25 and 50 $\mu g/m^3$ and extreme values appear less likely than with the first group.

It would appear reasonable to explain these differences not, as Graedel does, on the basis of whether known sources were sporadic or continuous, but in this case in terms of the nature of the sources constituting the distribtuion for each sector. The easterly sector's greater than average variance would seem explicable in terms of multiplicity of sources, source types and factors affecting the variation in their intensity observed. For an area source such as Glasgow a variety of emission heights and cycles means that transport and dispersal mechanisms are considerably more complex to visualise and so for a given set of meteorological circumstances considerable variation can be expected. This is not necessarily the case for the other directions where the concentrations reflect a much simpler emission environment; perhaps the direction corresponding to Glengarnock Steel Works is a case in point. Given a fairly regular emission intensity the observed concentration at Linwood shows less variation on average.

The importance of the Glasgow Area as a large and fairly variable source of SO_2 is thus confirmed. However, for a more detailed analysis of the behaviour of the pollution plume transported from here and other sources it is necessary to consider the effect of wind speed.

Table 7.3 Average Smoke Concentrations and Number of Observations for the Given Wind Speeds and Directions (With Summary of 'Calm' Pollution)

AVERAGE SMOKE CONCENTRATIONS AND NUMBER OF OBSERVATIONS FOR THE GIVEN WIND SPEEDS AND DIRECTIONS (WITH SUMMARY OF 'CALM' POLLUTION)

NO. OF DAYS WITH NO WIND DIRECTION DATA 0
NO. OF DAYS WITH DIRN. DATA BUT NO SPEED DATA 0
NO. OF DAYS WITH WIND DATA BUT NO SMOKE DATA 124

WIND SPEED DIRN	CALM	5,6	7,8	9,10	11,12	13,14	15,16	17,18	19,20	21	OVERALL
345 - 14	37.2	21.4	17.4	11.6	13.0	3.5	9.0	32.0	17.0	1.0	23.4
	54	22	19	16	16	6	6	1	2	1	143
15 - 44	43.4	41.2	40.7	20.3	11.3	8.3	10.2	33.0	10.0	16.0	35.4
	131	78	59	31	26	15	6	4	5	2	357
45 - 74	52.0	44.8	35.6	30.2	25.5	25.5	19.2	17.4	18.1	13.7	35.0
	155	238	253	194	155	86	51	33	19	6	1190
75 - 104	49.8	40.6	40.2	39.6	30.1	27.4	31.5	28.0	38.0	0.0	38.8
	80	122	141	108	90	34	16	7	1	0	599
105 - 134	57.4	46.4	36.3	37.8	34.4	26.9	18.6	22.2	10.0	25.3	40.8
	54	58	66	41	29	17	9	5	1	3	283
135 - 164	57.2	24.8	31.8	23.3	23.2	18.4	18.5	16.0	13.0	8.8	28.9
	39	40	58	30	29	20	21	10	1	5	269
165 - 194	34.8	24.6	27.1	21.6	18.8	15.5	12.8	12.5	19.5	13.7	21.2
	44	74	59	73	63	38	46	35	11	20	463
195 - 224	29.3	31.5	21.8	20.5	22.0	18.4	18.4	18.3	17.6	18.6	16.0
	125	124	156	166	151	121	105	65	63	117	1193
225 - 254	47.1	24.4	20.6	18.3	17.7	15.5	16.4	14.1	11.6	14.3	22.2
	211	227	262	179	186	142	105	94	63	94	1563
255 - 284	34.7	22.3	15.3	15.5	13.9	12.2	9.7	14.3	13.8	9.1	18.2
	186	123	157	116	128	93	92	48	33	66	1042
285 - 314	31.8	22.9	16.4	12.2	14.6	7.1	13.1	6.9	8.1	9.8	17.4
	89	67	82	57	57	36	37	26	17	21	489
315 - 344	31.1	17.7	10.3	16.4	12.2	9.9	10.2	4.8	2.0	16.5	18.8
	51	28	32	14	12	10	5	4	1	2	159
OVERALL	41.0	32.5	26.9	23.6	20.6	17.2	15.7	15.1	14.7	13.5	26.0
	1219	1201	1344	1040	943	618	499	332	217	337	7750

NO. OF DAYS WITH ZERO WIND SPEED :- 890 AVERAGE POLLUTION LEVEL FOR SUCH DAYS :- 59.2 (SUM OF SQUARES:- 6920601.0)
NO. OF DAYS WITH WIND SPEED 4 KTS. OR LESS: 2109 AVERAGE POLLUTION FOR SUCH DAYS: 49.2 VARIANCE: 3078.9 STD. DEV.: 55.5

Table 7.4 Average SO_2 Concentrations and Number of Observations for the Given Wind Speeds and Directions (With Summary of 'Calm' Pollution)

AVERAGE SO_2 CONCENTRATIONS AND NUMBER OF OBSERVATIONS FOR THE GIVEN WIND SPEEDS AND DIRECTIONS (WITH SUMMARY OF 'CALM' POLLUTION)

NO. OF DAYS WITH NO WIND DIRECTION DATA 0
NO. OF DAYS WITH DIRN. DATA BUT NO SPEED DATA 0
NO. OF DAYS WITH WIND DATA BUT NO SO_2 DATA 160

WIND SPEED DIRN	CALM	5,6	7,8	9,10	11,12	13,14	15,16	17,18	19,20	21	OVERALL
345 - 14	66.2	45.7	33.2	39.4	47.2	33.7	45.3	21.0	39.5	17.0	50.2
	53	22	19	16	16	6	6	1	2	1	142
15 - 44	72.5	77.3	84.3	60.8	55.2	43.5	44.0	78.3	44.8	37.0	71.0
	132	78	59	21	36	15	6	3	4	2	356
45 - 74	78.9	88.3	82.1	75.1	70.3	76.1	61.1	61.9	49.6	38.5	77.6
	153	236	250	194	153	83	51	32	18	6	1176
75 - 104	74.6	78.8	83.3	78.1	70.5	73.4	64.9	72.4	90.0	0.0	77.2
	80	122	142	108	89	35	16	7	1	0	600
105 - 134	80.2	81.5	73.3	76.8	66.3	72.5	48.1	50.0	86.0	48.3	74.6
	53	58	66	41	29	17	9	5	1	3	282
135 - 164	86.7	58.0	66.6	61.3	57.8	67.7	53.6	60.0	18.0	45.6	64.7
	39	39	59	45	30	20	21	10	1	5	269
165 - 194	46.8	42.8	50.0	46.6	43.0	47.7	38.7	49.3	36.6	30.8	44.5
	44	74	59	73	63	39	46	35	11	20	464
195 - 224	45.7	45.9	39.7	37.9	37.0	35.4	36.6	36.5	35.3	32.2	38.5
	125	124	156	164	151	121	105	64	63	117	1190
225 - 254	49.7	39.1	35.9	31.5	31.0	31.8	26.4	27.0	20.3	25.9	34.3
	210	224	262	179	185	142	105	94	63	94	1558
255 - 284	51.9	45.9	37.6	33.3	31.8	37.3	26.4	25.7	22.6	24.4	37.1
	187	123	157	116	128	93	92	48	33	66	1043
285 - 314	61.9	42.6	36.6	33.3	27.9	34.7	33.5	26.6	30.5	21.3	38.8
	89	67	83	58	57	36	37	26	17	21	491
315 - 344	70.0	44.1	51.9	25.7	49.6	64.2	29.4	24.3	59.0	28.5	53.3
	51	27	32	14	12	10	5	4	1	2	158
OVERALL	62.3	60.1	56.4	50.9	46.0	45.9	37.0	37.3	30.6	28.6	50.9
	1216	1194	1344	1039	939	617	499	329	215	337	7729

NO. OF DAYS WITH ZERO WIND SPEED :- 875 AVERAGE POLLUTION LEVEL FOR SUCH DAYS :- 69.6 (SUM OF SQUARES :- 7472152.0) NO. OF DAYS WITH WIND SPEED 4 KTS. OR LESS: 2091 AVERAGE POLLUTION FOR SUCH DAYS: 65.4 VARIANCE: 2916.9 STD. DEV.: 54.0

7.3 Wind Velocity

An analysis of the relationships between wind velocities and pollution was also carried out. Tables 7.3 and 7.4 show pollution data grouped into wind direction and wind velocity classes on the basis of four pollution allocations per day. In other words the daily values were attributed to each of the four wind observations. Over a long time period the obvious errors this technique introduces are minimised and a clearer picture is obtained than would otherwise be apparent using vector mean values.

Smoke can be seen to be particularly susceptible to wind dispersal. Overall, concentrations fall from just under 60 $\mu g/m^3$ in calm conditions to levels below 15 $\mu g/m^3$ in winds over 20 knots. Such a maximum at low wind velocities is characteristic of low level sources such as domestic chimneys. Higher level emissions would displace this maximum to higher wind velocities, a phenomenon noted below with SO_2 pollution. For each of the twelve directional categories maximum values were observed during calm and light wind conditions, with a fairly consistent diminution of concentrations with increasing wind speed. Rapid dilution is apparent with windspeeds over 10 knots although, for some directions, a slight increase with stronger winds can be seen. This may, or may not, be significant and could be related to downwash from local sources although, on the basis of the data available, it is impossible to draw such a conclusion.

Sulphur dioxide appears to be less susceptible to wind dispersion than smoke. During light wind conditions ($\leq$ 4 knots) SO_2 concentrations exceeded their mean by only 30% as opposed to a corresponding figure for smoke of 90%. Among other things, this suggests that the emission of sulphur dioxide in the area occurs in such a manner as to inhibit dilution much more effectively than smoke. Basically, this is because sulphur dioxide emissions predominantly occur from tall stacks which are designed to maintain the plume as discrete as possible for as long as possible. Such plumes are relatively buoyant, a feature which minimises dispersal in the lower levels of the atmosphere. The maximum concentration in each category is not exclusively tied to calm conditions as was observed with smoke values. This implies a potential for the transport of SO_2, in relatively undispersed form, for considerable distances yielding high concentrations, both occurrences which will be dealt with later.

Most mathematical models of the dispersal process suggest that ground level concentrations vary inversely with windspeed such that a doubling of wind speed should halve the concentrations observed. By considering the overall wind speed/concentration graph of Fig. 7.5 the approximate validity of this contention is apparent. However, the decline in concentrations appears rather less than might be expected. This could be due to the location and intensity of the major sources upwind. A more likely explanation is that with strong winds effective plume rise will be curtailed, resulting in a prolonged tail such as that described. This is allowed for in the well known CONCAWE formula (Brummage, 1968) and would explain the phenomenon.

As mentioned above, the maximum concentration for some directions occurs in windspeeds of 5-8 knots. This is not a phenomenon exclusive to West Central Scotland. Leone et al (1966) found a similar relationship in the New York Area while Sonkin and Khrapachenko (1973) studied the problem for Chita in the Soviet Union. Stability appears to be the key to understanding the problem. It would seem that with windspeeds below 2 metres per second increased stability reduces air pollution while it increases concentrations in winds over 3 metres per second. Lucas (1975), for example, claims that for 20% of the time (with winds less than 1.75 m/sec.) a chimney 200m high can have an effective height of more than 1,340 metres. In other words under calm and light wind conditions the effective height of a chimney is assumed to be almost infinite. One of the two reasons why this is patently untrue, namely entrainment by cooler surrounding air, has already been mentioned. The second, and most important, the effect of free air inversions, will be dealt with shortly. It is sufficient for the present however to note that plume buoyancy is responsible for peak values not occurring, as with smoke, in calm conditions.

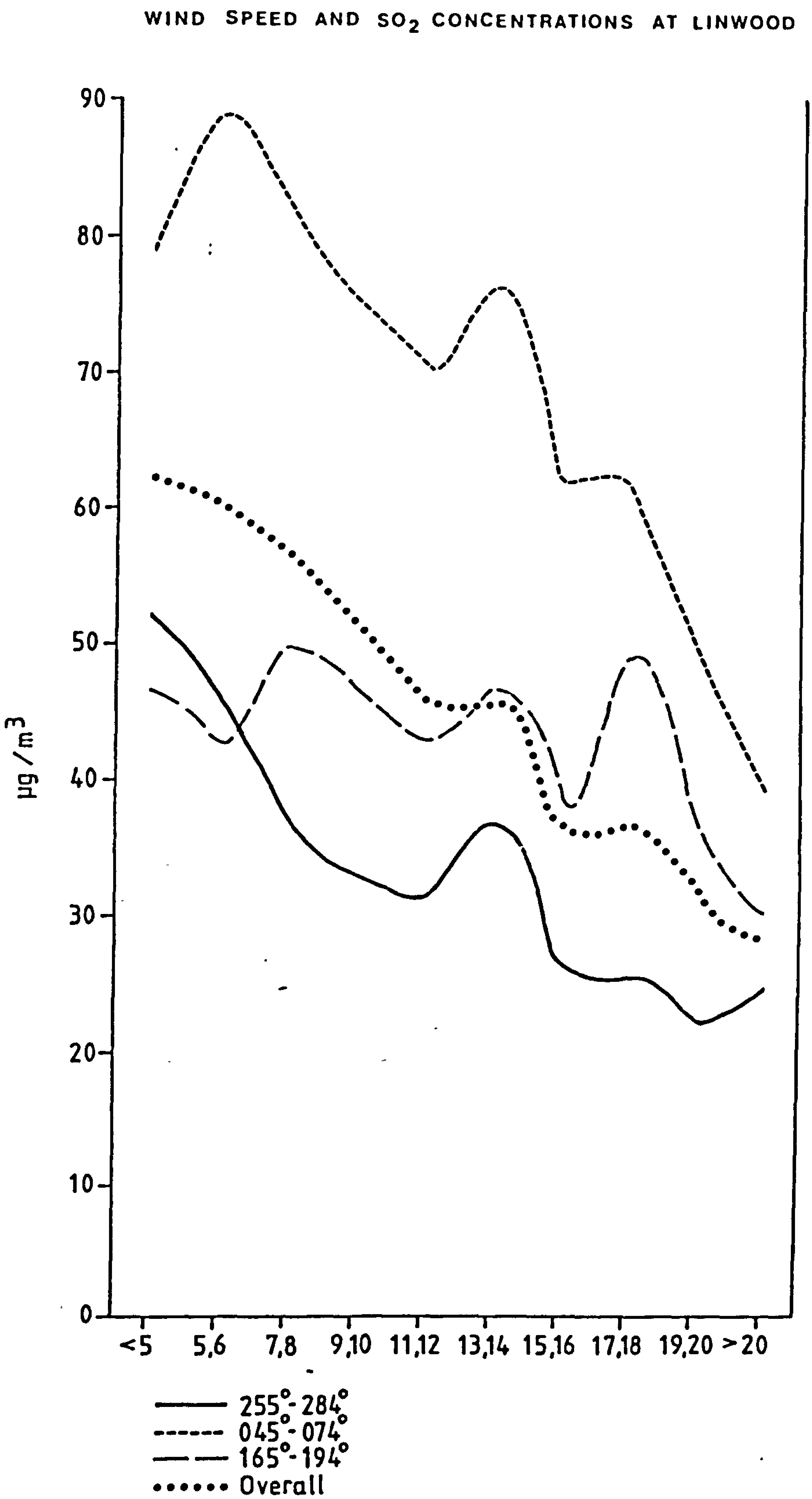


Fig. 7.5 Wind Speed and SO_2 Concentrations at Linwood

Table 7.5 SO_2 and Daytime Winds (12h, 18h)

Direction	Speed										
	Calm	5,6	7,8	9,10	11,12	13,14	15,16	17,18	19,20	21+	Overall
345 - 14	83.9 28	49.3 15	39.7 14	35.3 9	47.9 13	33.7 6	45.3 6	21.0 1	39.5 2	17.0 1	54.5 95
15 - 44	88.6 59	80.1 31	75.3 37	75.1 17	48.1 17	38.7 11	34.3 3	55.0 1	44.8 4	37.0 2	73.8 182
45 - 74	88.0 59	102.1 86	84.4 96	76.4 97	74.9 91	71.2 47	60.0 37	60.6 26	50.0 11	43.0 3	79.8 553
75 -104	87.8 31	76.0 40	85.5 64	68.8 59	65.6 49	71.4 25	61.2 13	65.4 5	0.0 0	0.0 0	74.9 286
105 -134	75.5 23	86.5 30	77.5 42	74.7 23	65.7 15	72.0 13	47.0 7	59.5 4	86.0 1	59.0 2	75.0 160
135 -164	94.4 17	60.8 16	70.2 33	64.7 25	56.3 20	72.3 15	55.5 13	66.4 9	18.0 1	54.3 3	67.3 151
165 -194	57.5 20	46.2 25	47.9 29	51.3 37	45.9 43	46.7 23	33.8 27	52.0 19	67.0 2	28.8 9	46.7 234
195 -224	58.8 35	59.0 52	44.2 83	38.1 94	37.2 88	36.0 73	33.6 60	35.3 42	29.8 40	33.1 68	39.7 635
225 -254	64.0 57	43.8 78	39.3 128	34.4 89	34.5 101	32.6 86	24.7 63	27.7 52	18.7 39	23.3 59	35.3 752
255 -284	62.1 70	46.3 48	39.4 78	36.4 78	31.5 102	34.6 66	25.8 69	24.1 29	22.0 20	27.2 44	36.6 604
285 -314	58.7 46	45.7 49	38.7 70	38.1 40	27.9 49	37.2 30	36.9 32	25.2 23	28.6 11	23.0 12	38.7 362
315 -344	83.3 24	50.8 16	53.6 24	24.5 10	53.1 9	65.4 9	16.5 2	34.3 4	59.0 1	28.5 2	56.4 101
Overall	74.0 469	64.9 486	56.8 698	51.1 578	45.8 597	45.2 404	35.9 332	37.7 214	28.7 132	28.9 205	51.1 4115

Table 7.6 SO_2 and Night time Winds (00h, 06h)

Direction	Speed									
	Calm	5,6	7,8	9,10	11,12	13,14	15,16	17,18	19,20	21+	Overall
345 - 14	46.5 25	38.0 7	14.8 5	44.7 7	44.0 3	0.0 0	0.0 0	0.0 0	0.0 0	0.0 0	41.4 47
15 - 44	59.5 73	75.4 47	99.4 22	43.5 14	68.4 9	56.5 4	53.7 3	90.0 2	0.0 0	0.0 0	68.2 174
45 - 74	73.2 94	80.4 150	80.6 154	73.8 97	63.6 62	82.6 36	64.0 14	67.8 6	48.9 7	34.1 3	75.7 623
75 -104	66.3 49	80.1 82	81.5 78	89.2 49	76.6 40	78.3 10	81.0 3	90.0 2	90.0 1	0.0 0	79.3 314
105 -134	83.7 30	76.1 28	66.0 24	79.4 18	67.0 14	74.0 4	52.0 2	12.0 1	0.0 0	27.0 1	74.1 122
135 -164	80.8 22	56.0 23	62.1 26	57.1 20	60.8 10	53.8 5	50.4 8	34.5 2	0.0 0	32.5 2	61.3 118
165 -194	37.8 24	41.0 49	52.0 30	41.8 36	36.8 20	49.1 16	45.8 19	46.1 16	29.9 9	32.4 11	42.3 230
195 -224	40.6 90	36.4 72	34.7 73	37.7 70	36.8 63	34.6 48	40.5 45	38.9 22	44.7 23	30.9 49	37.2 555
225 -254	44.4 153	36.6 146	32.6 134	28.7 90	26.7 84	30.4 56	29.0 42	26.2 42	22.8 24	30.2 35	33.4 806
255 -284	45.8 117	45.7 75	35.8 79	27.0 38	32.7 26	43.8 27	28.1 23	28.2 19	23.5 13	18.8 22	37.8 439
285 -314	65.3 43	34.4 18	25.1 13	22.7 18	28.5 8	22.3 6	11.4 5	37.0 3	33.8 6	19.1 9	39.3 129
315 -344	58.1 27	34.4 11	46.9 8	28.8 4	39.0 3	53.0 1	38.0 3	0.0 0	0.0 0	0.0 0	47.8 57
Overall	54.9 747	56.9 708	56.1 646	50.5 461	46.2 342	47.3 213	39.1 167	36.4 115	33.6 83	28.1 132	50.7 3614

This explanation is, however, contradicted by the existence of double pollution maxima, particularly on eastern and southern wind categories. This can either be related to varying emission types, one hot and one cold, or to two different dispersal environments, one stable and the other unstable. To test the validity of the latter the data was dissected into daytime and night-time winds, Table 7.5 and 7.6. It can be seen that the double maxima has largely disappeared from the observations based on day time winds (12h, 18h) although they appear more pronounced on winds corresponding to more stable nocturnal conditions (06h, 24h). It is suggested, therefore, that some of this night maxima reflect distant origin pollution transported under stable, stratified conditions and fumigated upon passing over the relatively warm urban area of Glasgow. While evidence of this phenomenon does not appear to be available in other research, a related mechanism has been documented by Lyons and Cole (1976) where stable flow across Lake Michigan in summer is destroyed by thermal turbulence on land with severe fumigation of trapped pollutants.

Enhanced pollution concentrations essentially occur in two ways. Either pollution generated around the monitor is prevented from dispersing by the thermal structure of the atmosphere, or pollution generated at a distance from the monitor is transported in a fairly discrete entity to the monitor where its effects are felt. The former case is shortly to be examined, but the considerations outlined above have demonstrated the paramount importance of dynamic factors in explaining short term variation in pollution levels. Using routine observations it has been possible to identify general and specific sources, variations in their intensity, differences in their susceptibility to wind action, differing behaviour patterns related to changing meteorological conditions and comparison with other areas in the world has been made. The importance of wind in pollution studies has thus been emphasised to the same degree as did Manley (1952) in referring to its general climatic importance.

> "The climate of the British Isles and the consequent appearance of the landscape owes much to latitude, notably in respect of the great seasonal variation in the amount and intensity of light ; but still more is due to our position and maritime surroundings especially with regard to wind".

CHAPTER 8

INVERSIONS OF TEMPERATURE (i)

8.1 The Nature and Influence of Temperature Inversions

Air temperature normally falls with increasing height above ground level up to the level of the tropopause. Under certain meteorological conditions, however, a reversal of this lapse can occur, producing, within the troposphere, a layer of air in which temperature increases with height. Where this phenomenon occurs at a sufficiently low altitude to interact with the pollutant dispersal process then such an inversion of temperature is able to exert a strong control on ground level concentrations of all types of airborne pollution. This is achieved by a reduction, due to the presence of very stable conditions at a particular altitude, in the vertical depth of air throughout which pollutants are mixed. Accordingly, inversions are very relevant in many aspects of industrial location, such as chimney design, and merit special attention in respect of their strength, height, persistency and frequency of occurrence.

The almost completely enclosed nature of the Clyde Basin described in Chapter One makes pollutant trapping in association with temperature inversions more significant than would otherwise be the case. This lateral constriction imposed by relief considerations, combined with a reduction in vertical mixing due to the existence of temperature inversions, has in the past been responsible for many parts of the area experiencing smoke and SO_2 concentrations above the levels at which adverse health effects are apparent. The area has a reputation for bad fogs, some of which are frequently cited in air pollution literature (Chalmers, 1930). As recently as 1964/65 concentrations between 3,000 and 4,000 $\mu g/m^3$ were observed for both smoke and SO_2 during such fogs, and as has been demonstrated earlier, a considerable potential for high pollution periods continues to exist despite the marked air quality improvements of recent years.

Almost invariably these episodes occur during winter fogs. Intense radiational cooling appears to result in an inversion at about 125m O.D., with katabatic downflow of cold air from the adjacent moorlands and highland areas. Halstead (1973) has noted the similarities in vertical temperature structure which then exist with that of the infamous London smog of 1952. From this he concludes that intense trapping, even of buoyant plumes, by low level temperature inversions is a feature of the Glasgow Basin. Personal observations during freezing fog conditions, made on the Gleniffer Braes instrumentational sites, confirm this conclusion and it would thus appear that periods of enhanced concentrations in the area are related as much to the relief configuration of the Glasgow Basin as to the meteorological conditions interacting with it.

8.2 Surface Inversions

The most common situation giving rise to a temperature inversion is that which occurs due to nocturnal cooling of air in close proximity to a cold ground surface. Where clear skies encourage maximum outgoing radiation, particularly in light winds, the feature is enhanced, perhaps sufficiently to survive the turbulent and thermal mixing of the following day. Continuation beyond two or three days is most unlikely, since the conditions favouring outgoing radiation at night also favour maximum incoming radiation during the day.

Hosler (1961) investigated low level inversion frequency for the contiguous United States, eventually using it as the basis of a 'climatic/geographic' classification of the country. He found a marked difference between observations made at coastal and inland locations. Overall frequencies were calculated from twice daily radiosonde ascents which were assumed to be representative of either daytime or night-time conditions. Allowance was also made for day length and, in the case of coastal locations, for excessive marine influences.

For much of the Atlantic seaboard annual frequencies of 40-70% were noted while values up to 90% were more common in the interior. The coastal stations appeared to exhibit a lower frequency due to the advection of warm, moist air from the sea, particularly at night. The element of instability thus introduced inhibited surface inversion formation and therefore contrasted with more interior locations where radiation considerations alone prevailed. This was particularly evident along the Gulf of Mexico where the coastal/inland contrast was well marked. A different set of factors was seen to be operating on the Pacific coast, and along the extreme north-eastern seaboard on the Atlantic coast. The relatively cool waters offshore in these cases tended to produce cool breezes which increased stability and were observed to result in more frequent surface inversion formation.

Hosler's work is relevant in again recalling the errors inherent in utilising distant radiosonde data as an analytical tool in the Glasgow Basin. The question as to what degree conditions at either Shanwell or Long Kesh are representative of those in the Glasgow Area naturally arises.

Table 8.1 shows that surface based inversions were observed at Long Kesh on 46% of the nights during the six year study period. The comparable figure for Shanwell was 48%. In contrast to these frequencies which were based on the midnight radiosonde ascent in both cases, surface inversions based on the noon ascents were relatively scarce. At Long Kesh such daytime surface inversions were observed only on 4% of the noon ascents while the comparable figure for Shanwell was only slightly higher at 5%.

There is a slightly greater frequency of surface inversions, therefore, at all times of day at Shanwell as opposed to Long Kesh. Though the difference detected in the above analysis is only a matter of a few per cent, even this may be significant if interpreted on the basis of Hosler's findings outlined above. The North Sea is shallower and less saline than the Atlantic Ocean. It does not receive the full force of the North Atlantic Drift. The North Sea, therefore, exhibits a greater seasonal range of temperature than does the sea around Ireland. Most importantly, the North Sea is colder than the Atlantic in winter. It is conceivable therefore that the introduction of moist, warm oceanic air into the lower atmospheric levels will be less marked at Shanwell than at Long Kesh. Thus, while both stations have a coastal location on the eastern side of a landmass, marine influences may be more marked at Long Kesh than at Shanwell. This would have the effect of inhibiting the formation of surface inversions more at Long Kesh, explaining the slightly reduced frequencies observed.

A longer period of observations based on the thermohygrograph network within the Basin would have enabled the question of the validity of using radiosonde data from the two locations above to be settled fairly conclusively. Unfortunately only 20 months of a record existed. This enabled only a crude comparison to be done which nevertheless

Table 8.1 Surface Inversions at Shanwell and Long Kesh 1971-77

	Shanwell	Long Kesh
Midday Radiosonde		
Number of Occurrences	112	87
% of Midday Observations	5%	4%
Mean SO_2 at Linwood ug/m^3	82 µg/m^3	73 µg/m^3
Midnight Radiosonde		
Number of Occurrences	1,048	1,014
% of Midnight Observations	48%	46%
Mean SO_2 at Linwood ug/m^3	54 µg/m^3	55 µg/m^3

yielded figures relatively close to the longer term averages, quoted above. The overall duration of surface inversions during the 20 month period, in the Glasgow Basin, was within 3% of the long term (6 year) value for Long Kesh and 4% of that for Shanwell. This would seem to lend validity to the use of Shanwell and Long Kesh data within the Clyde Basin. Intuitively, Long Kesh typifies a climate where advection is dominant over the radiation regime, while Shanwell typifies a regime where radiational controls are more important, if not quite dominant. Given that such a slight difference in surface inversion frequencies between these two cases exists then it would seem reasonable to conclude that the situation at, say, Abbotsinch, would be roughly intermediate between the two. Accordingly, there is some justification for believing radiosonde data from these two stations to be reasonably representative of conditions in the Glasgow Area.

Work elsewhere in Europe would appear to suggest that surface inversion frequency continues to increase from west to east, beyond the confines of Scotland. Schwegler (1967) found surface inversions in Munich on 78% of the nights while McIntyre and Thornton (1978) claimed that for that part of the U.S.S.R. south of the Arctic Circle the overall inversion frequency ranged from 60-80%. It would thus appear that surface inversion frequency is closely related to continentality, lending further credibility to Hosler's seemingly rather ambitious use of the term 'climatic/geographic' in describing regions delimited using this criterion.

8.3 Surface Inversions : their role in air pollution studies

One view of the role of surface inversions in pollution dispersal was given recently by D.H. Lucas (1975) who stated "that in any realistic situation now or in the foreseeable future, unsatisfactory concentrations of sulphur dioxide can be avoided by an appropriate increase in chimney height." It must be admitted that this assertion was principally concerned with the actual emission height being above the usual inversion level rather than implying that buoyancy alone could be used to penetrate low level inversions. However, with shallow, surface based inversions penetration by even moderately buoyant plumes is common and because of this the observed trapping effect of these phenomena is not great. During nights when a nocturnal surface inversion existed at Shanwell, smoke and SO_2 averages at Linwood were 34 and 54 $\mu g/m^3$ respectively, not markedly different from the long term averages of 30 and 50 $\mu g/m^3$ respectively. Midday surface inversions, though few in numbers were much more effective agents in trapping pollutants, particularly smoke. These conditions produced values of 76 and 82 $\mu g/m^3$ respectively for smoke and SO_2. It might seem reasonable to suggest that in part this may reflect increased low level emissions, especially from domestic and commercial sources, during this portion of the day. Perhaps it could also be postulated that such inversions, having survived the tendency to dissipate due to thermal and mechanical turbulence in daylight, might be more effective lids than their weaker nocturnal counterparts.

Scriven (1967) has expressed the maximum ground level concentration which may be expected when the assumed Gaussian dispersion model is subjected to trapping at low altitudes.

$$C_{max} = C_{conmax} \left[1 + \exp \left\{ 4 \frac{h}{h_e} \left(1 - \frac{h}{h_e} \right) \right\} \right]$$

where

C_{conmax} = maximum of a coning dispersion with no trapping

h = inversion height

h_e = effective stack height

This formula suggests that the worst effect of an inversion would be a doubling of concentrations, this occurring when the inversion height and plume rise coincided. Intuitively this seems correct since if some or all of the plume rises through the inversion it is most unlikely to contribute to ground level concentrations.

In one important respect the deficiencies of using only 24 hours average values of pollutant concentrations are apparent. This relates to the suggestion that intermittent surface inversions, in association with a free air subsidence inversion permit a build-up of trapped pollutants to accumulate in the air intermediate between the two inversions. During daytime periods of vertical mixing these trapped pollutants could be mixed down to ground level, as could any pollutants trapped the previous night, under the surface inversion. In what amounts to successive periods of fumigation the whole of the mixing layer up to the base of the subsidence inversion becomes polluted, a process repeated as long as anticyclonic activity remains dominant. A moment's reflection will reveal that these short bursts of fumigation, while producing high short term concentrations, will over the course of a day have no more noticeable effect on average concentrations for the 24 hour period than would have been the case in the absence of any surface inversions. Had hourly or total sulphur monitoring data been available it would seem certain that these short duration bursts of high pollution would have been apparent, as they were on Holzworth's (1972) data on the New York Thanksgiving Week Episode, (Fig. 8.1), and as described by Halstead (1976). Fig. 8.2 shows such a period when the effect might well have been expected although the daily averages cannot show any effect other than the longer term build up of pollution beneath the subsidence inversion, although a more complex mechanism may

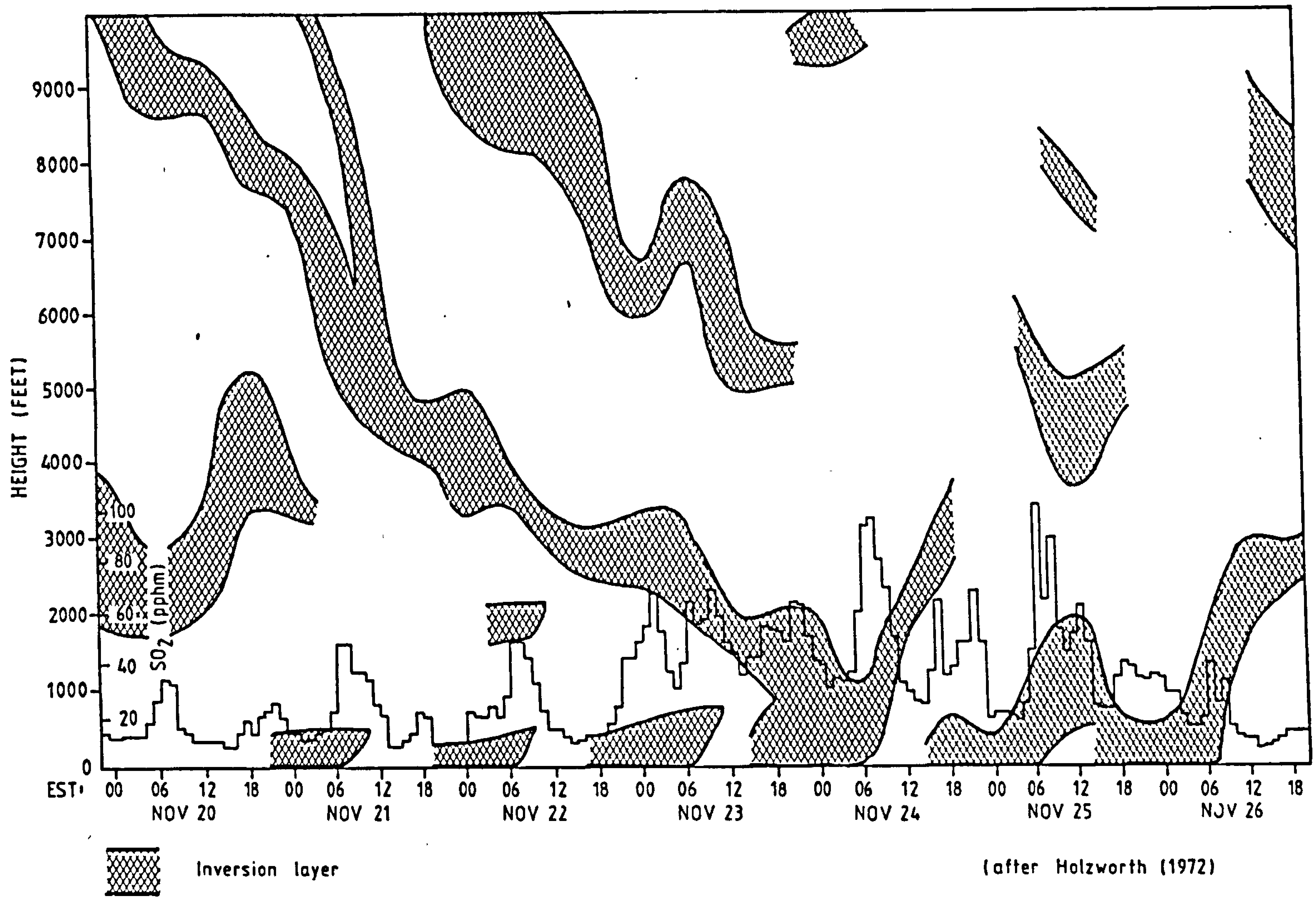


Fig. 8.1 Inversion Behaviour and Short Term Changes in SO_2 Concentration During the New York Thanksgiving Week Episode

INTERMITTENT SURFACE INVERSIONS BELOW A SUBSIDENCE INVERSION AT LONG KESH AND CORRESPONDING SMOKE AND SO_2 CONCENTRATIONS AT LINWOOD

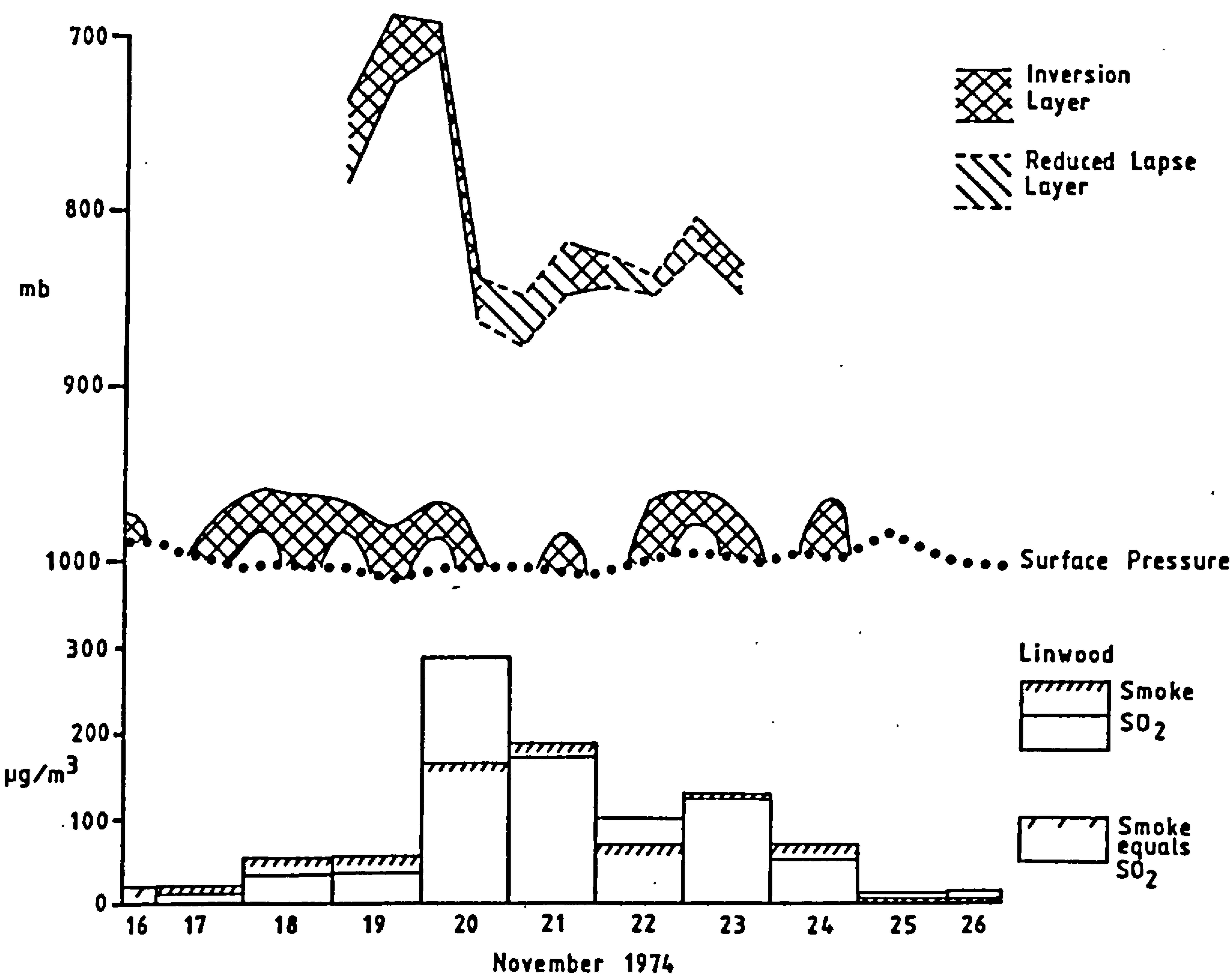


Fig. 8.2 Intermittent Surface Inversions Below a Subsidence Inversion at Long Kesh and Corresponding Smoke and SO_2 Concentrations at Linwood

well be operative in this case. Thus it might be concluded that although the surface inversions have not directly trapped high level emissions, their very impersistence is a factor in causing high concentrations to be measured, although only over short durations, at surface monitors.

Such a mechanism adds fuel to the continuing controversy between advocates of high chimneys and their opponents. Under the circumstances described above, at least in fairly calm conditions, high, hot effluent has not achieved a better dispersal than would a less expensive lower, cooler effluent system. Where a wind exists it is however, possible that high level effluent could be exported from the region during low level inversion occurrences without having its effect felt at the surface. The element of uncertainty involved goes part of the way to explaining the doubts expressed by such bodies as the United States Environmental Protection Agency concerning the effectiveness of high stack dispersal policies. Of course the question of the necessity of constructing a 240m chimney for Inverkip Power Station likewise could be raised at this juncture.

8.4 Surface Inversions in an Urban Dimension

It has already been described how light winds, cloudless skies and anticyclonic conditions in general encourage the development of surface inversions. However, these conditions also correspond to those which, in an urban atmosphere, favour the development of an urban heat island. It is now appreciated that a quite distinctive microclimate exists in cities on such occasions due to the effects of their surface structure, artificial heat generation and modification of their local atmospheric composition. Considerable research has been conducted into the phenomenon in the last twenty years and the magnitude and importance of the urban heat island is now fairly well understood (see Chandler, 1971). Much of the original work was done in London by Chandler (1961, 1962(a), 1962(b), 1964(a), 1964(b), 1965) although heat island effects have also been documented for small cities such as Leicester (Chandler, 1967), Sheffield (Garnett, 1965), and Reading (Parry, 1970). Of greater relevancy to this study, however, has been a short period investigation based on temperature traverses within the built-up area of Glasgow (Hartley, 1977). Despite the limitations imposed on the time span available for this investigation the author found urban-rural temperature contrasts up to 7.8^{o}c, a magnitude comparable with any of the other studies mentioned. The most favourable circumstances were found to be those described above when a surface based inversion might be expected to develop in the surrounding rural area. Within the city, however, the existence of a warm pool of air close to the surface would obviously inhibit the formation of a surface inversion.

Clarke (1969) investigated the nocturnal layer in and around Cincinnati, Ohio, during periods when urban heat island effects were marked. He showed that when there was a strong inversion over the rural areas upwind of the city two distinct regimes were apparent over the city: (a) the shallow unstable boundary layer, heated from the surface, and (b) a very stable layer aloft. Downwind of the city three categories of air masses existed : a stable rural surface layer, the unstable 'urban plume' and the stable layer aloft. Similar results were obtained from helicopter observations over Leningrad by Vdovin (1974) who clearly saw their relevance when he claimed, "these stratification features over the city create conditions for the spreading of contaminant that differ from those prevailing on the outskirts."

One implication of the climatic modification caused by urban influences is that with a reduction or even elimination in the frequency of surface inversions then amelioration of the air pollution environment is possible. Ewing (1972) investigated the thermal output per unit area necessary for a city to prevent surface inversions forming all year round. Assuming ideal conditions for inversion formation, a clear sky, high temperature (30^{o}c) and a low vapour pressure (9 mb) he estimated that several cities in the U.S. satisfied his inversion avoidance criteria, at least in winter. Despite criticism which partially invalidated his results (Jayaweera, 1973) a reduction in winter surface inversion frequency was confirmed by Baker and Enz (1969). Lower per capita consumption of energy on this side of the Atlantic does not preclude the strong possibility that pollutant trapping below a surface based inversion is more likely in rural and semi-rural areas than in the city centre itself.

In summary, therefore, it has been shown that surface inversions occur most frequently in association with the nocturnal cooling of air in contact with a cold ground surface. Seldom do they persist during the day although in such circumstances their trapping effect seems more marked. On a larger scale the most significant factor determining frequency of occurrence appears to the interaction of land and sea influences the effects of which can be seen elsewhere in the world also. On a more local scale special considerations relating to urban heat islands are apparent, and these may have particular relevance to the location of the three monitors downwind of the city under anticyclonic easterly drift. Often, however, surface inversions exist simultaneously with free air inversions, making the effect of each difficult to disentangle. It is to this second category of inversion, the free air inversion, therefore, that attention must now be given.

CHAPTER 9
INVERSIONS OF TEMPERATURE (ii)

9.1 High Level Trapping and the Tall Stack Controversy

Debate continues regarding the most effective way of minimising ground level concentrations of sulphur dioxide. On the one hand are the advocates of tall chimneys who maintain that such a policy results in emissions being diluted to acceptable levels before reaching the ground. Their opponents, on the other hand, favour tackling the problem at source by limiting the sulphur content of fuel such that the potential for high ground level concentrations does not exist. In the United Kingdom, the first of these viewpoints has held the ascendancy for the last twenty five years, an approach summarized by Nonhebel (1969) in his report on the impact of Inverkip Power Station, then at the planning stage.

"The only method accepted anywhere in the world at present for dealing with SO_2 from large power stations is to discharge the flue gases through tall chimneys and at as high a temperature as is practicable, i.e. discharge hot and high."

In this statement Nonhebel was merely restating the theoretical basis of the Chimney Height Memorandum to the Clean Air Act (Ministry of Housing and Local Government, 1963) which laid down guidelines designed to ensure that effluent was well dispersed before being stirred downwards towards ground level. More recently Lucas (1975) has further claimed that 'for all practical situations tall chimneys provide effective control of ground level concentrations'.

The effectiveness of this policy has been increasingly open to question in recent years, largely on the grounds that conditions have changed such that area sources are dominant rather than point sources. In essence this means that while on a scale of the order of tens of kilometres high stack dispersal is successful, when viewed on a larger scale, over hundreds of kilometres, this is not always the case. It is not difficult to envisage an isolated situation where a sufficiently buoyant effluent emitted from a realistically high chimney will prevent surface concentrations exceeding a realistic standard for a distance of many kilometres in the vicinity of the source. There is, however, a strong case for believing that this control strategy merely exports the problem downwind to add to the control problem of adjacent regions or countries. Long distance transport of pollution is now a well known phenomenon (see Holt-Jensen, 1973, Nyberg, 1970, Breeding et al, 1975) and will be discussed with respect to this study in Chapter 14. However, it might be pertinent to suggest that one consequence of the tall chimney policy in use in Britain is that a great many more regions interact in the pollution dispersal problem. One effect of this is that control policies designed purely for internally produced pollution within a given airshed are virtually obsolete. This reasoning is largely behind the U.S. Environmental Protection Agency view that tall chimneys are not effective when the overall pollution of very large areas is considered. They have therefore concentrated on the alternative strategy of limiting the emission of sulphur dioxide. This lead is now being followed by the European Economic Community (see Chapter 2) and marks the evolution of the air pollution problem into one with an international dimension rather than one concerned principally with local conditions, as has been the case in the past.

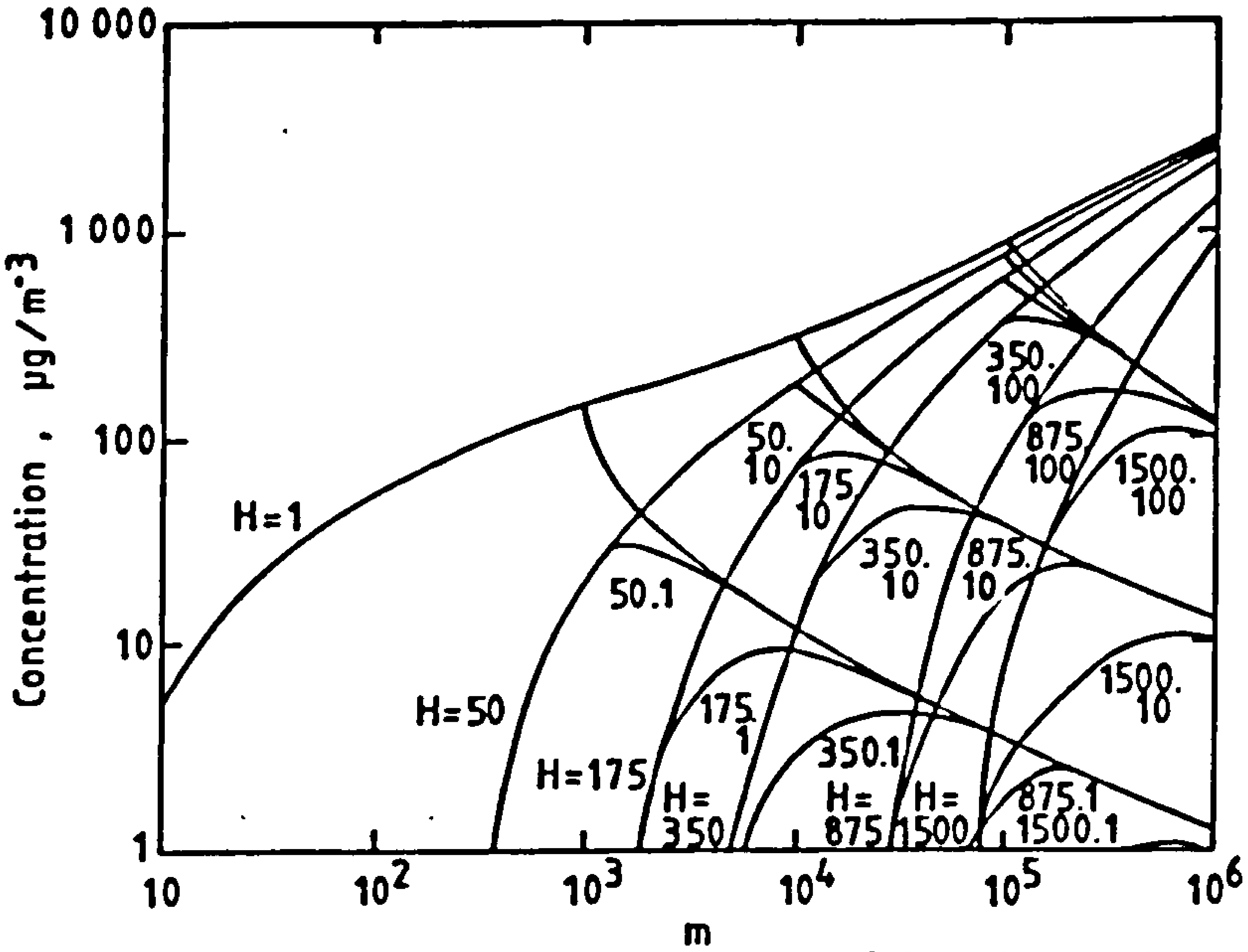
One of the basic reasons why increasing use is being made of the more expensive emission control policy is a growing awareness of the effect of high level inversions of temperature. The nature of these inversions, and the manner in which they trap the high level effluent from tall chimneys is described below. What is important firstly is an appreciation of their effect in inhibiting even the ameliorative effects of the most buoyant pollution plume on ground level concentrations.

It might seem ironical to suggest that evidence pointing to the disadvantages of tall stack dispersal can be found in Lucas' (1975) paper which advocates the contrary viewpoint. Two figures are reproduced from this paper as Figs. 9.1 and 9.2. In Fig. 9.1 the variation of concentration with distance from the source is shown for a neutral atmosphere. This is shown for various effective chimney heights and various sizes of area sources. It can be seen that the effect of increasing effective chimney height is to project the point of maximum concentration further away from the source and also to render this maximum considerably less than that which would be observed with a smaller effective chimney size. For all cases a continuing fall in concentration with increasing distance past this value is apparent.

This is not the case for Fig. 9.2 which shows the same features for a neutral atmosphere capped by a stable layer at 400m. Although a similar reduction in maxima can be noted with increasing chimney height, beyond about 50 kms. for the case of the 10 km. city the effect of differing emission heights is not noticeable. In fact a constant concentration is observed with increasing distance, regardless of chimney height. As such the concentration observed with such trapping expressed as a ratio of the concentration which would have been observed in a neutral atmosphere increases steadily with distance. This was confirmed mathematically by Ragland (1976), and as such has widespread implications which Lucas does not deal with.

Firstly it is clear that since concentrations do not fall off with distance no further dispersal of the plume is occurring. This suggests that this fairly discrete pollution package can be transported by light wind action for great distances so long as the atmospheric conditions remain unchanged. In fact the only effective constraints may be the various scavenging processes which remove SO_2 from the atmosphere (see Chapter 2). Should this stability break down, however, eddy cells will attack and disperse the trapped effluent, but not before high concentrations have experienced for a time at the surface.

Secondly, the transport of such trapped pollution may itself contribute to background levels on reaching another area of emission. Lucas assumes that a background level



(after Lucas (1975).

Where two figures are shown against a curve the first indicates the effective chimney height (m), and the second the extent of the area source in km^2.

Fig. 9.1 The Variation of Concentration with Distance, Uniform Neutral Atmosphere

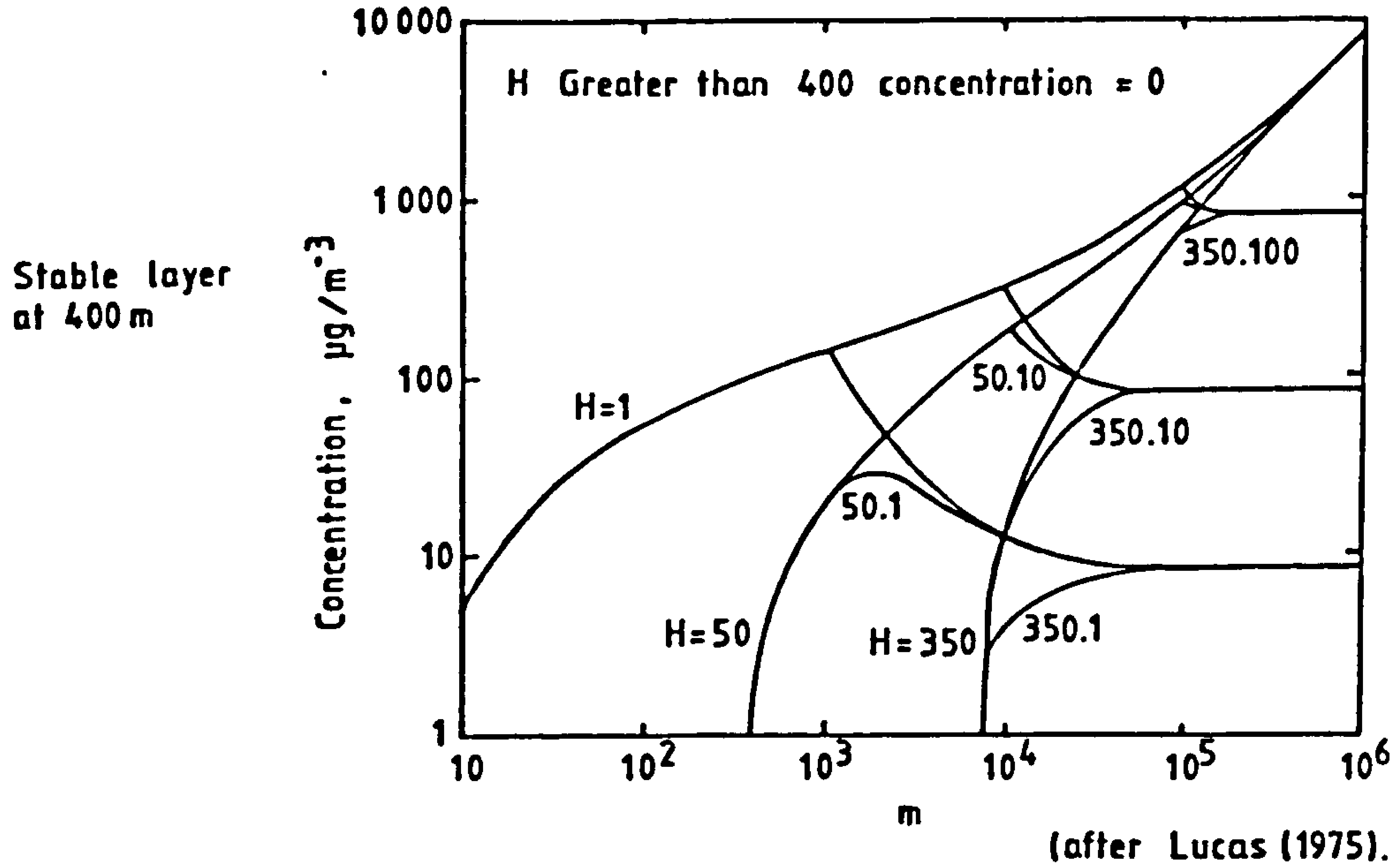


Fig. 9.2 The Variation of Concentration with Distance, Neutral Atmosphere to a height of 400m.

of zero exists within his emission areas and that no effluent has been imported. That this is unrealistic in view of the right hand side of his diagram (9.2) needs no further emphasis. What is also conceivable, however, is that material entering the city under the inversion lid will be subjected to fumigation in the thermal plume overlying the city and will thus be the cause of high concentrations being observed there. That this mechanism has been observed operating over Glasgow will be shown from the Linwood data in Chapter 11.

It would thus appear that control policies based on high stack dispersal are not effective under certain inversion conditions. It should be emphasised, however, that they are of considerable use in minimising the maximum concentration levels observed from any given installation. It may be that this is the principal criterion which is used, a suggestion partially confirmed by Keddie and Williams (1974) who state that normally an industrial chimney is constructed on the basis that the contribution to ground level concentrations will at no time and place exceed 500 $\mu g/m^3$ for more than about three minutes. Such a value, however, may well be exceeded during fumigation periods when effluent, projected many hundreds of metres into the atmosphere, and trapped at the base of a high level inversion, is brought back to the surface (Garnett, 1971).

With particular reference to West Central Scotland O'Hare (1974) has noted that at least on a regional scale high stack dispersal would be a more successful pollution procedure were it not for the development of high level inversions. Similarly, Halstead (1973) has called for further research into the role of these phenomena in affecting pollution dispersal with a view to assessing more accurately the impact of new industrial developments. Further investigation of the nature and behaviour of free air inversions is therefore the next logical step in this study.

9.2 Free Air Inversions

In addition to surface based inversions of temperature, reflecting local modification of the layer of air close to the ground, stable layers can also exist at any level up to the tropopause. Two types of free air inversion appear to predominate, although within each category considerable variation exists as regards structure, persistency, and the effectiveness of the stable layer in trapping pollution beneath it.

Frontal inversions are frequently found at the temperature discontinuity between different air masses. In this context they must be seen as an exception to the rule of thumb suggested by Crowe (1971) that 'uplift and convergence tend to liquidate and disperse inversions.' Frontal inversions are a product of the convergence of two air masses, one warmer than the other. Pushed on by a following wind the warm air overrides the cold air wedge producing the discontinuity at height which ultimately becomes a warm front at the surface. Further upwind a cold front is produced in a related manner by the undercutting cold air as it seeks to 'catch up' with the initial cold air sector of the depression. Warm, cold, or the closely related occluded fronts may be identified on a high proportion of soundings where a cyclonic wind trajectory is in evidence. Since the features are associated most often with moving depressions they seldom linger more than a day and undergo rapid changes in altitude which render them fairly ineffectual agents when it comes to trapping pollution. They may, however, have some significance in cases where the depression becomes slow moving or stationary.

Of much more significance for the trapping of pollutants is a second category of temperature inversions associated with anticyclonic activity. The outward spiral of air at the surface of an anticyclone is fed by a subsiding central core which is itself renewed by high level return of air. During the descent of this air it is warmed adiabatically by compression producing a thick inversion layer which can trap all but the most buoyant plumes under certain circumstances. As subsidence passes through its peak the inversion level falls, characteristically by about 0.6-0.8 cms/s, (Holzworth (1972), Sweeney (1979)), thus reducing the mixing height to a minimum at the point where surface pressure is highest. Thereafter, a rise in the inversion height occurs as pressure declines and the anticyclone moves away or decays. Such a mechanism implies a time span of a few days since anticyclones are characteristically slow moving features which disrupt the west to east progression of weather in middle latitudes. The behaviour and persistence of subsidence inversions is thus of central importance in pollution studies and merit special attention which is accorded to them in Chapter 12.

Before concluding this subsection note should also be taken of a third category of inversion which to some extent is a hybrid version of the previous two. This concerns the case of pre-frontal subsidence in which air is forced to subside by an advancing front. As a result of this a smaller inversion can be produced below the level of the frontal inversion and it may be this lower one which is the effective trapping level for pollution. Meteorological Research Flights through frontal zones (see Freeman, 1961) revealed the existence of a wedge of extremely dry air, with relative humidity as low as 5%, between the bounding surfaces around 800mb. Such a set of circumstances can only be explained by the pre-frontal subsidence described above.

9.3 Subsidence Inversions and Air Pollution

The relationship between anticyclonic weather types and enhanced pollution concentrations has long been known. In Britain the connection was established via particulate pollution during fogs by such researchers as Absalom (1954) and Meetham (1955) who, working during that period between the 1952 London Episode and the passage of the Clean Air Act in 1956, found a strong correlation between ground level concentrations and surface pressure. Similar findings for the case of SO_2, always considered more significant than smoke in the United States, were outlined by Holzworth (1962) who also noted the prime importance of blocking anticylcones, especially those with a warm ridge aloft. Since then the forecasting of air pollution potential in the U.S. has been largely synonymous with forecasting anticyclonic activity, a feature outlined by Smith (1975).

Awareness of the importance of the subsidence inversion was shown by Meade (1954) who found peak concentrations occurring beneath the central area of the anticyclone. More explicitly Lawrence (1967) found a relationship between concentrations and the inversion height over five winters. Perhaps the most comprehensive evidence, however, was presented by Holzworth (1972) who extensively monitored the 1966 Thanksgiving Week episode in New York City (Fig. 8.1). The descending subsidence inversion is quite clear and is accompanied by rising SO_2 concentrations which peak at 2660 $\mu g/m^3$ when minimum height is reached. In this case the falling inversion merged with the surface based one to give a stable layer almost 600 metres in depth. Successive nocturnal inversions are also apparent although there must be some doubt as to whether these features, measured at Kennedy Airport, also existed over Manhattan. Nevertheless their role in further constricting the mixing height is clear. Halstead (1976) has also pointed out their effect in promoting successive periods of fumigation of the effluent trapped above them ; evidence nearer home for this was seen in the preceding Chapter.

Analysis of the available data for the three monitors and the various sources of meteorological data confirms the validity of the conclusions above. Visual evidence in the form of plotted values of surface pressure and ground level concentrations were sufficiently convincing to suggest that higher levels of SO_2 almost invariably occur when surface pressure exceeds the mean of 1013 mb. To some extent this is due to the greater tendency for easterly and north easterly winds which exists under these conditions, but, even allowing for this a relationship seems to hold. The format in which the data was stored rendered a direct correlation between surface pressure and concentrations rather inconvenient. However, frost frequency was taken as a measure of anticyclonic activity in any given month. Though far from perfect this would seem a reasonable substitute since the most favourable conditions for frost match those for surface inversion development and are provided best in anticyclonic type weather. A correlation of 0.758, significant at 0.00001 was obtained between monthly averages of smoke and frost, and a lesser value of 0.301, significant at 0.0051, for the case of SO_2. Sample sizes in each case were 72. In this analysis, as in many others throughout this study, therefore, the increased tendency for smoke to be trapped by low level inversions, as opposed to the more buoyant SO_2 emissions, can be noted. It would be wrong to read too much into these figures, however, since during anticyclonic weather in winter, emissions due to space heating probably increase sharply.

Fig. 9.3 shows a period of anticyclonic weather during November/December 1973. The steady, if irregular, fall in the subsidence inversion can be noted, and can be seen to be mirrored by a rise in concentrations. Once peak subsidence has occurred the reverse takes place and concentrations fall back to their 'normal' levels. This provides substantiation for the theoretical behaviour of pollution described above and shows how closely pollution concentrations react to a change in the available mixing height.

INVERSION LAYERS AT SHANWELL AND CORRESPONDING SMOKE AND SO_2 CONCENTRATIONS AT LINWOOD DURING ANTICYCLONIC PERIOD NOV-DEC 1973

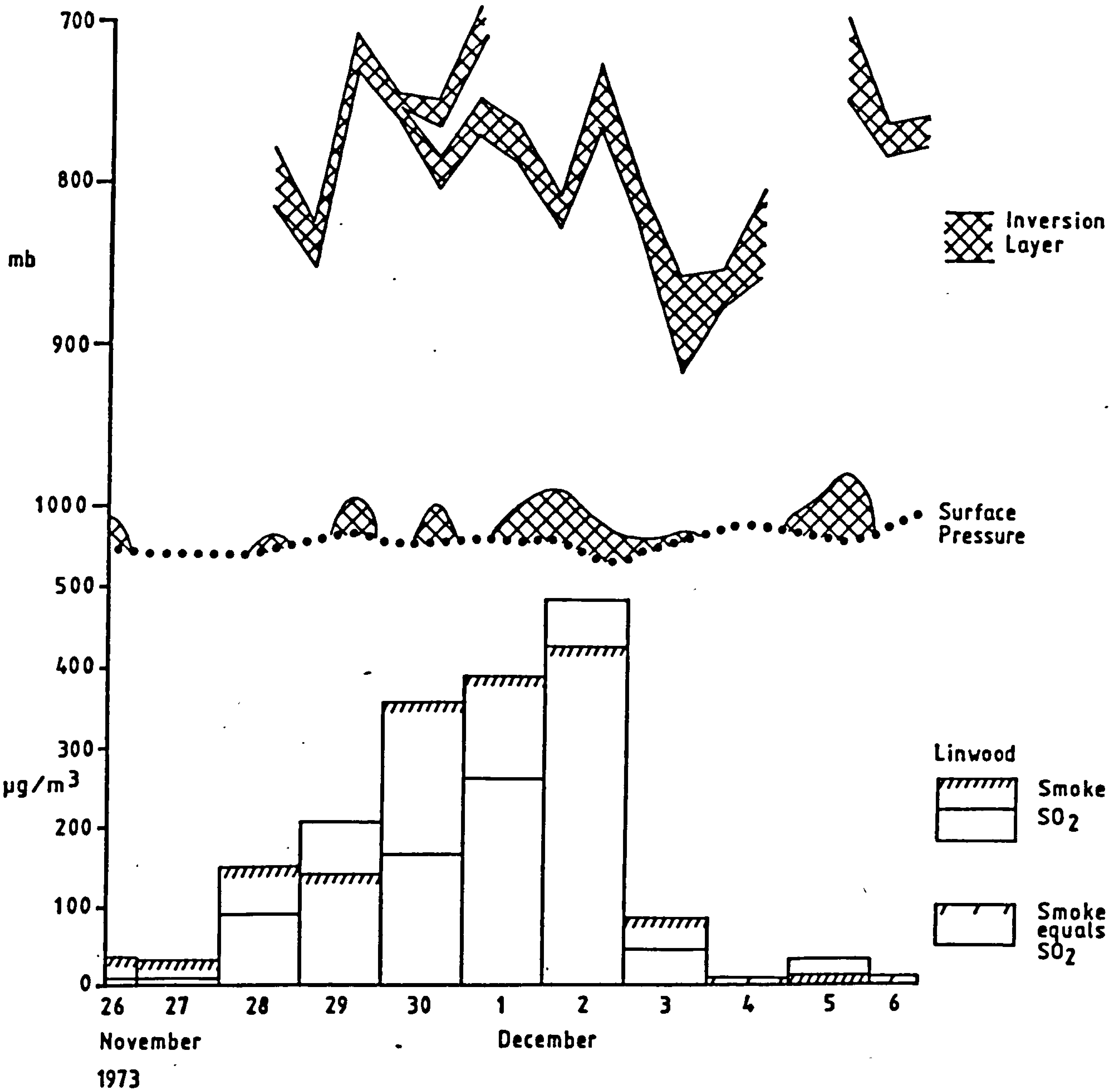


Fig. 9.3 Inversion Layers at Shanwell and Corresponding Smoke and SO_2 Concentrations at Linwood During an Anticyclonic Period Nov./Dec. 1973

9.4 Calculation of the Mixing Height

In order to investigate the relationship between pollution dispersal and inversion trapping, information is necessary concerning the heights at which these stable layers are operative. Allied to information on frequency and persistency, such data would enable better prediction of ground level concentrations both as a short term early warning mechanism (see Kumar and Djurfors, 1977) and as the longer term planning tool called for by Weddle (1969). Unfortunately such data is not easily accessible due to the format of the Upper Air Report from which it must be extracted. With the exception of the standard isobaric surfaces of 1000 mb., 850 mb., 700 mb., and 500 mb., nothing in the way of height information is contained in the report and the various temperature and dew point soundings are expressed in terms of the atmospheric pressure at the point in question. Except for the rare cases where the top or base of an inversion occurs at one of these standard pressure surfaces, therefore, most departures from the standard lapse rate are tabulated in terms of two pairs of temperature and pressure readings. These correspond in general to the base and top of the inversion layer.

The initial reaction to this difficulty is to convert the pressure values directly into height values on the basis of an assumption of the standard lapse from a surface pressure of 1013 mb., the standard surface pressure. Such a course would be wrong for two reasons. Firstly, a considerable variation in surface pressure is in evidence, ranging from 960 mb. to 1040 mb. at Long Kesh during the period. Such a range could lead to calculations in error by several hundred metres. Secondly, however, is the problem of temperature. Although a better approximation to the true mixing height was obtained using the pressure difference between the surface and the inversion this also was found to be subject to error because of the variation in temperature of the intervening column of air. Analysis of the plots of partial thickness for the layer 1,000-500 mb. at Shanwell showed a considerable variation ranging from almost 5,700 metres during the exceptional summer of 1976 down to 5,080 during the cold winter of 1971/72. Since such a variation is too large to permit accurate estimates of the mixing heights to be obtained consistently it was considered essential that both temperature and pressure data be utilised in any calculation of mixing height.

One such formula, widely used for calibrating altimeters, was found to contain these features. In its original form this is given by

$$p\ (z) = p\ (o)\ \exp\left(\frac{-gz}{R\bar{T}}\right)$$

where p (z) is the pressure at height z,p(o) is the surface pressure, g is the acceleration due to gravity, R is the Gas Constant, and $\bar{T}$ is the mean temperature for the intervening column of air in ^{o}K where

$$\bar{T} = \frac{T\ (z)-T\ (o)}{2}$$

The equation was solved for z. A pilot study revealed a good agreement with more formal tephigram analysis and the technique was thus adopted as the method of determining heights from D.A.R. data.

A Fortran IV programme was written which searched the data bank for those soundings having inversions or isothermals below about 600 mb. Surface inversions were not considered in this analysis in view of their secondary role as trapping agents outlined in Chapter 8.1. At the same time the programme also evaluated the average mean vector wind direction for the day in question. Where this quantity fell in the range 001^{o}-180^{o} the programme selected the Shanwell data as being the more appropriate, and where the wind fell in the sector 181^{o}-360^{o} Long Kesh was automatically selected. This followed the precedents set by Comer (1976) and Halstead (1973) when dealing with high level inversions in the study area. Only the lowest inversion was considered in the calculations which involved almost 60,000 punched card images.

The file created thus enabled smoke and SO_2 values for particular days to be examined in relation to the height of any inversion existing at the time of the two radiosonde ascents. This was considered significant in the light of previous research by Lynn (1976) who examined the role of inversion height in influencing the dispersal of photochemical pollutants in the Los Angeles Basin. An interaction with the surrounding mountains was found such that, when the inversion lid was low enough to nearly 'meet' the mountains, pollution was funnelled along the base of the inversion causing vegetation damage far from the urban areas. A similar mechanism would seem to be responsible for forest damage in the vicinity of Prague (Hanibal, 1977). Situated in an almost completely enclosed basin these effects would be all the more pronounced due to the persistency of subsidence inversions in a climate with marked continental influences due to the influence of Voikoff's Ridge (Borisov, 1965).

Evidence for relief influences acting in conjunction with inversions such that a synergistic effect on concentrations resulted suggests that Weddle (1969) may have been correct in suggesting that air pollution problems are most complex in Central Scotland not because of any one factor, such as relief, micro-climate and the location of the major sources, but rather from the combination of all three factors which produces a combined effect greater than the sum of the influences taken separately.

CHAPTER 10

CRITICAL INVERSION HEIGHTS

10.1 Effective Limitations on Mixing Height

The mixing heights calculated using the method described in Chapter 9 were examined to ascertain over what general range, and with which specific heights, did noticeable effects on ground level concentrations of smoke and sulphur dioxide occur.

On those occasions when an inversion was present below 4,000m. mean smoke and sulphur dioxide values were 29.6 $\mu g/m^3$ and 53.4 $\mu g/m^3$ respectively. This is almost identical to the overall average values of 29.3 $\mu g/m^3$ and 53.0 $\mu g/m^3$ respectively, implying that the actual existence or otherwise of an inversion is not in itself significant. This conclusion at first seems incongruous with previous conclusions. However, part of the answer can be found if only the lower 1,000m.of the atmosphere is considered.

Then

	Mean Concentration	No. of Cases	Standard Deviation	
Inversion	33.5	541		Smoke
< 1,000m	62.8	541		SO_2
Total	29.3	2,149	36.5	Smoke
Population	53.0	2,149	44.0	SO_2

The sampling distribution of the means is known to be normally distributed (Norcliffe, 1977) such that:

$$\sigma_x = \frac{\sigma}{\sqrt{N}} \sqrt{\frac{N_p - N}{N_p - 1}}$$

where

$\sigma_{\bar{x}}$ = standard deviation of sampling distribution of the means

σ = standard deviation of total population

N_p = total population size

N = sample size

This enables the sample mean to be expressed in standard units about the population mean.

$$z = \frac{\bar{x} - \mu}{\sigma}$$

The value of z can then be used to evaluate the proportion of area of the normal curve which lies below the z value. This in turn represents the probability that the sample is randomly drawn from the total population. The difference between the means when an inversion below 1,000m. existed was thus found to be significant with a probability of over 99.9% that mean concentrations of both smoke and SO_2 were not randomly drawn from the total population.

Similar conclusions could have been obtained working in terms of log concentrations which, as noted in Chapter 5, are normally distributed.

A significant difference is not found when an inversion below 2,000 metres is considered. This suggests that only inversions below about 1,000m. exert a significant influence on ground level concentrations. This value should be seen in relation to work elsewhere on plume rise. Djurfors (1972) calculated that the maximum rise, in stable, calm conditions, of the plume from a 2,400 MW power station would be about 760m. Lucas (1975) claimed that ' once stable layers are higher than 1,000m. they cease to have important effects.' Both of these findings are not contradicted by the calculations above which tend rather to reinforce them although the distance between monitor and radiosonde discourages too great an emphasis on absolute values of mixing height.

10.2 The Interaction between Inversion Height and Relief

The almost continuous rim of hills surrounding the Glasgow Basin has already been mentioned in Chapter 1. To the north the Campsie Fells and Kilpatrick Hills rise to plateau levels between 400m. and 600m. while to the south the Renfrew Heights and Kilbirnie Heights rise to plateaux between 300m. and 500m., altitudes similar to the eastern watershed towards the River Forth.

The existence of well marked erosion surfaces on these surrounding hills has long been known from measurements of altimetric frequencies, from sampling studies and also from studies concerned with measuring contour areas (Halstead, 1973). The two most importance surfaces isolated seem to occur at about 390m. on the lower volcanic hills and at about 700m. in the Highlands and Southern Uplands. In addition to identifying these, George (1958) also found less distinct terraces at 510m. and 580m. On a smaller scale the effect of such erosion surfaces could be likened to the effect of the San Gabriel and San Bernardino Mountains in restricting the dispersal of pollution from the Los Angeles Basin. Where the inversion height is just below the summit level concentrations might be expected to be significantly greater than if the inversion lid is just above, thereby enabling pollution to 'escape' from the basin (Lynn, 1976).

In order to examine this hypothesis the mean concentrations of smoke and sulphur dioxide occurring with specific inversion heights were analysed. On Fig. 10.1 the inversion height data for midnight is grouped into 100m. ranges and plotted against the corresponding pollution values. The number of observations in each category was generally in the range 50-100, below about 2,000m., declining to about 15 above 3,000m. The plot was discontinued at this level as the number of cases fell below acceptable values.

It can be seen that considerable variations in concentrations occur with inversions at different heights. Smoke concentrations exhibit this to a lesser extent than do SO_2 values which rise to 85 $\mu g/m^3$ with an inversion between 300m. and 400m. and fall to 35 $\mu g/m^3$ when the inversion

MIDNIGHT INVERSIONS VERSUS SMOKE AND SO_2 CONCENTRATIONS

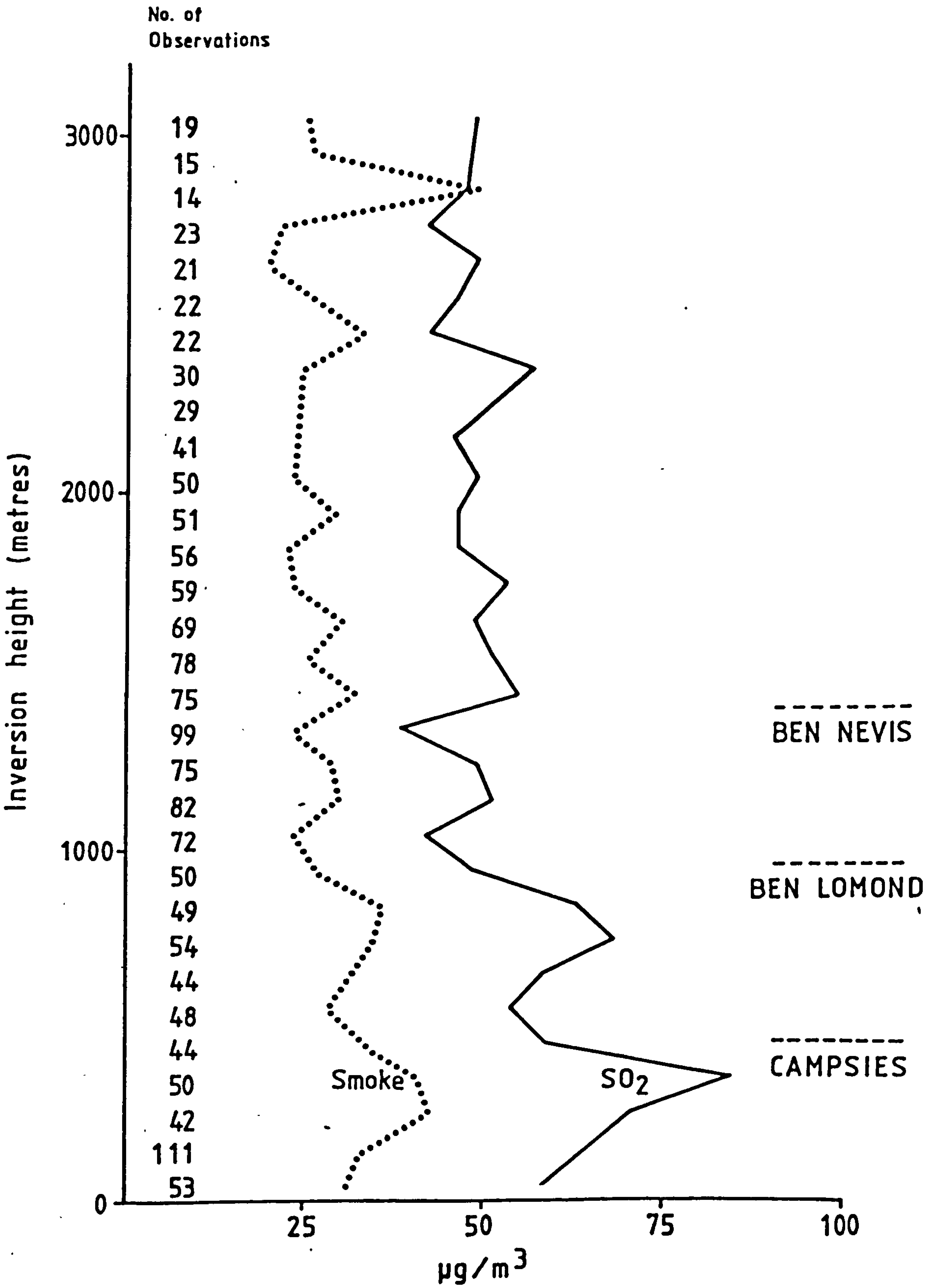


Fig. 10.1 Midnight Inversions Versus Smoke and SO_2 Concentrations

is between 1,300m. and 1,400m. The comparable range for smoke occurs in height categories over 2,500m. where averages are based on relatively few observations. This being so it was decided to assess the statistical significance of the individual occurrences in each 100m. height category making up the overall picture.

One way of doing this is to pose the following question. Given a total population of smoke and SO_2 data over six years what is the probability that the mean value of a given sample could have been drawn randomly from this population? In other words, with reference e.g. to the height category 0-100 m. for SO_2, how probable is it that a sample of 53 would yield a mean concentration value of 58.6 $\mu g/m^3$ or greater. This is a similar problem to the one tackled earlier in this Chapter, and again the method outlined by Norcliffe was employed. Z scores were worked out for each 100 metre sample and the corresponding probabilities ascertained. These are displayed for both smoke and SO_2 in Table 10.1. Occasions when there was less than a 1% chance of the sample having been randomly selected were considered to represent very significant departures from mean overall conditions, and it could be postulated that such deviations reflected additional influences on pollution dispersal.

Such significant departures from the overall picture can be clearly seen in the probability columns of Table 10.1 where the values fall below 1%. For these inversion heights the mean concentration of either smoke or SO_2 is anomalously high, there being less than one chance in a hundred that random sampling of the data would have produced such high values. It is suggested that these departures offer strong corroboration for one of the central hypotheses of this study, namely the existence of a complex interaction between the relief configuration and free air inversion regime in West Central Scotland as a strong control on air pollution dispersal.

Two distinct peaks can be seen on Fig. 10.1 for both pollutants below 900 metres. For smoke these occur at 200-300 metres with a lesser one at 800-900 metres. For

Table 10.1 A Statistical Justification of the Significant Inversion Heights in Fig. 10.1

Height Class	Sample No.	Sample Mean	Z Score	% Probability	Sample Mean	Z Score	% Probability	"Randomness" < 1% probable
2,900-3,000	15	26.1	-0.34	36.7%	45.2	-0.67	25.1	
2,800-2,900	14	48.4	1.96	2.5	42.0	-0.90	18.4	
2,700-2,800	23	21.7	-1.00	15.9	56.7	0.39	34.8	
2,600-2,700	12	19.6	-1.00	15.9	50.9	-0.21	41.7	
2,500-2,600	22	25.8	-0.45	32.6	45.2	-0.79	21.5	
2,400-2,500	22	32.7	0.44	33.0	42.0	-1.14	12.7	
2,300-2,400	30	24.5	-0.73	23.0	56.7	0.45	32.6	
2,200-2,300	29	40.5	1.66	4.9	50.9	-0.25	40.1	
2,100-2,200	41	23.7	-0.99	16.1	45.2	-1.11	13.3	
2,000-2,100	50	23.6	-1.12	13.1	48.7	-0.68	24.8	
1,900-2,000	51	28.7	-0.12	45.2	45.8	-1.14	12.7	
1,800-1,900	56	22.4	-1.43	7.6	45.8	-1.20	11.5	
1,700-1,800	49	23.2	-1.30	9.7	52.7	-0.05	48.0	
1,600-1,700	69	29.3	0.00	50.0	48.4	-0.85	19.8	
1,500-1,600	78	25.4	-0.96	16.9	50.8	-0.43	33.4	
1,400-1,500	75	31.6	0.56	28.8	54.0	0.19	42.5	
1,300-1,400	99	23.6	-1.59	5.6	38.2	-3.32	0.0	(SO_2) (i)
1,200-1,300	75	28.7	-0.14	44.0	49.0	-0.78	21.8	
1,100-1,200	82	29.5	0.05	48.0	51.0	-0.40	34.5	
1,000-1,100	72	23.2	-1.43	7.6	41.6	-2.15	1.6	
900-1,000	50	26.1	-0.63	26.4	48.8	-0.66	25.5	
800- 900	49	36.6	1.42	7.8	62.8	1.53	6.3	
700- 800	54	34.6	1.08	14.0	67.7	2.41	0.8	SO_2
600- 700	44	31.6	0.42	33.7	57.9	0.72	23.6	
500- 600	48	28.2	-0.21	41.7	53.4	0.06	47.6	
400- 500	44	32.5	0.58	28.1	58.0	0.74	23.0	
300- 400	50	40.2	2.14	1.6	84.5	4.96	0.0	SO_2
200- 300	42	42.7	2.40	0.8	70.5	2.52	0.6	Smoke SO_2
100- 200	111	32.7	1.00	15.9	64.1	2.64	0.4	SO_2
0- 100	53	31.5	0.44	33.0	58.6	0.91	18.1	

(i) Negative z scores yield probabilities of samples with mean values less than that specified.

(ii) Total Population Size = 2,149, mean smoke = 29.3 (σ = 36.5), mean SO_2 = 53 (σ = 45.4).

sulphur dioxide the features are more distinct, occurring at 300-400 metres and 700-800 metres. In view of the greater buoyancy imparted by its sources SO_2 would seem the more significant case, illustrating considerable trapping at these levels. Furthermore, of all the inversion layers considered in Table 10.1 it was these two which stood out as being fundamentally different, the lower one for both smoke and SO_2 and the higher one for SO_2 only. The adjacent categories constituting the lower peak were also significant for SO_2.

The capability for such enhanced trapping can be explained in terms of the altitudes at which it occurs. Both peaks occur within the ranges suggested by George (1958) at which the two most significant erosion surfaces occur, namely at 390 metres and 700 metres. The former occurs at the higher levels of the surrounding volcanic hills described earlier, and quite clearly this maximum is related to this. It would appear that this altitude is the critical altitude at which the surrounding lava plateaux lose their influence on pollution dispersal. When the lid rises above this height the pollution can escape into a greatly increased volume of air where greater diffusion can occur. By contrast, when the inversion is only a few metres lower, maximum trapping within the Basin seems to occur.

On a wider scale a similar phenomenon seems to occur with inversions around 700 metres. This height corresponds to the main erosion surface of the Highlands and Southern Uplands, some 35 kilometres distant. In the same way as the Glasgow Basin dimension gave way to the Central Valley dimension at the lower critical height, so this in turn permits ventilation of most of Scotland at this higher critical height. Perhaps the last vestiges of landform influence may be seen in the smaller third maximum at 1,100-1,200 metres, the level of the Highland peaks, themselves the vestiges of a major erosion surface. This peak is not marked enough to show up as significant in Table 10.1, however significant and nearly significant minima occur immediately above and below it suggesting that some inversion/relief interaction may be occurring. Further work however would be necessary to substantiate any inferences drawn on such inconclusive data.

It is thus quite clear that theoretical calculations of pollution dispersal which make no allowance for relief factors will be greatly in error due to the interaction between relief and vertical pollution dispersal described above. Furthermore the existence of such critical height information is of valuable use in the design of the emmission characteristics of major new sources. Obviously a considerable improvement in air quality would follow if plume rises of over 400 metres were common throughout the Basin. Inversion trapping of emissions below this level is principally responsible for the tendency for persistent pollution episodes already noted and also for the reputation for bad fogs which the basin had in the past.

The critical values outlined above can only be described in terms of the quality of data used to drive them. Halstead (1973) has suggested that additional low level inversions may be operative in the Glasgow Basin, not detected on the radiosonde data. Analysis of chopped light cloud base data from Abbotsinch would tend to support this. But more tangible evidence should perhaps be evident from the thermohygrograph data.

Between October 1st 1975 and June 1st 1977 the daily maximum temperature at Gleniffer Brae (250m.) exceeded that at Abbotsinch (2m.) on 58 occasions (9.5% of days). For the same time period the number of surface inversions at noon at Long Kesh was 38 (6.25% of days). Though not stricitly comparable, and of only 20 months duration, these figures suggest differences between the low level inversion regime in the Glasgow Basin, and that assumed on the basis of the radiosonde data alone. Had a more extensive thermohygro graph network been available, over a greater range of height, and for an extended time period it might well have suggested that additional low level inversions were present in the Glasgow Basin which were not apparent on the radiosonde ascents at either Shanwell or Long Kesh. As will be seen shortly this would be a useful source of explanation in relation to concentration peaks occurring with apparently very high inversion layers.

10.3 The Effect of Thermal and Turbulent Mixing

The instability caused by solar heating of the atmospheric layers close to the ground can promote vigorous upward dispersion of pollutants. According to Pack (1964) the depth of this well mixed layer can vary from more than 3,000 metres over desert areas to only a few hundred metres over forested lake country. But while the thermals of rising air often destroy surface based inversions they may fail to break through higher stable layers. More significantly, however, these convective eddies may pull pollution trapped beneath the base of these higher inversions back to ground level, producing for a time high concentrations, the circumstance known as fumigation.

A daytime analysis of inversion heights and SO_2 concentrations was conducted in a similar fashion to that already outlined for the midnight radiosonde observations. Fig. 10.2 shows both sets of data in conjunction. A similar trapping pattern can be seen for both time periods, especially above 800 metres. Below this level daytime trapping heights would appear to be somewhat lower than their nocturnal counterparts. Reasons for this are not clear, but they would seem to be related to the greater difficulty of trapping SO_2 during daylight hours when convective mixing seeks to disperse it.

In the range 2-3 km. marked concentration peaks are apparent on the mid-day plot, these are absent from the comparable midnight categories

The rather small numbers of observations involved, ranging from 14 to 27 prevents firm conclusions being drawn from these height ranges. The values furthermore do not appear to be significant if the criteria used in Table 10.1 are applied. Nevertheless, probability values of as low as 2% are readily obtained, suggesting that there may be some basis for interpretation, however tentative the conclusions must remain.

The most obvious suggestion is that these peaks might

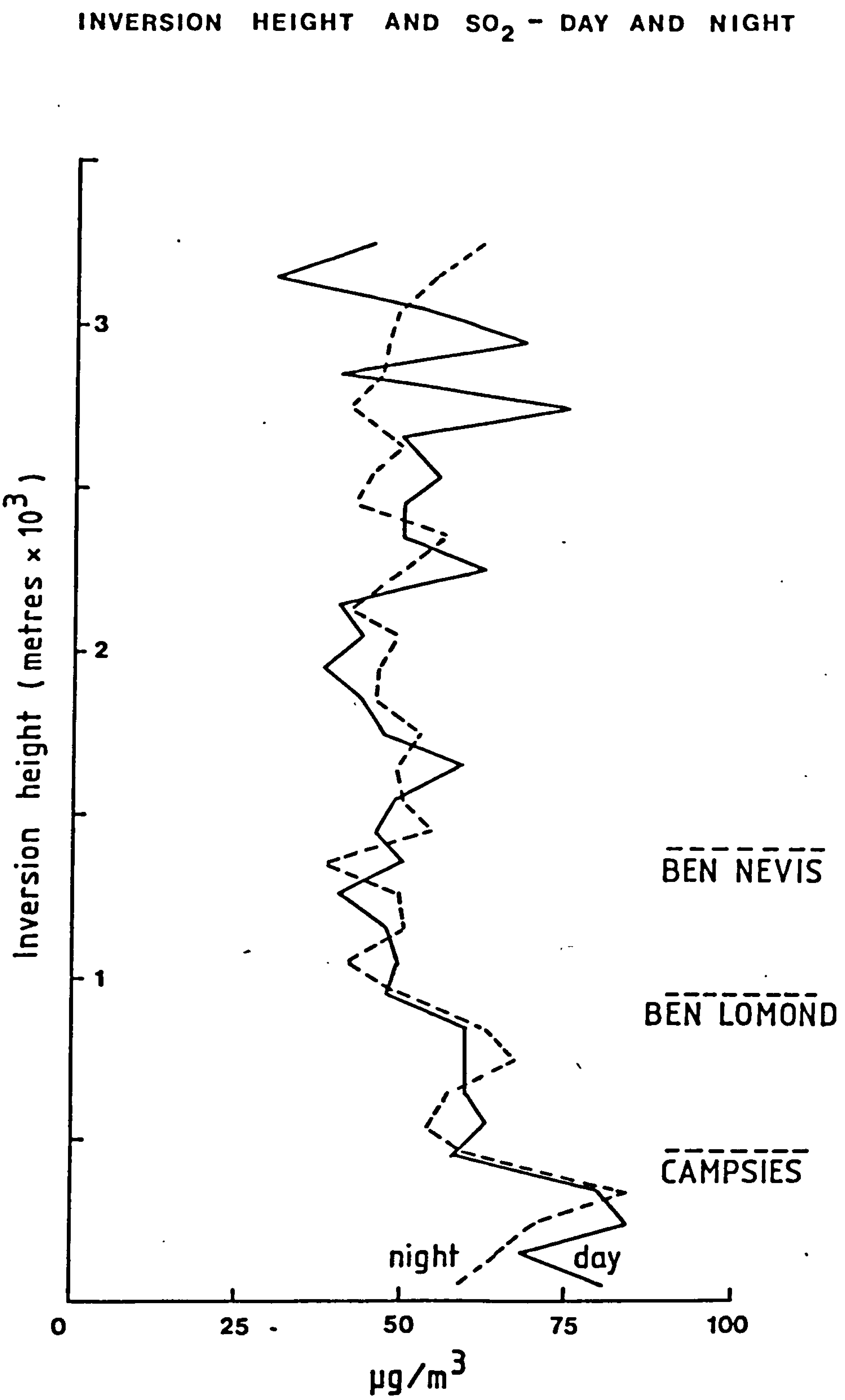


Fig. 10.2 Inversion Heights and SO_2 - Day and Night

be considered as pointing to evidence of fumigation below high level inversions. For at least some of these observations this may well be the case. Kumar and Djurfors (1977) have described the daily upward growth of the mixing layer, terming it the 'thermal boundary layer.' They found that the height to which thermally induced mixing extended varied according to time of day and time of year. Minimum values characteristically occurred during January while a number of unlimited mixing height cases were recorded from June to August. Such convection could mix pollution trapped beneath high altitude inversions back to ground level, causing higher than expected ground level concentrations.

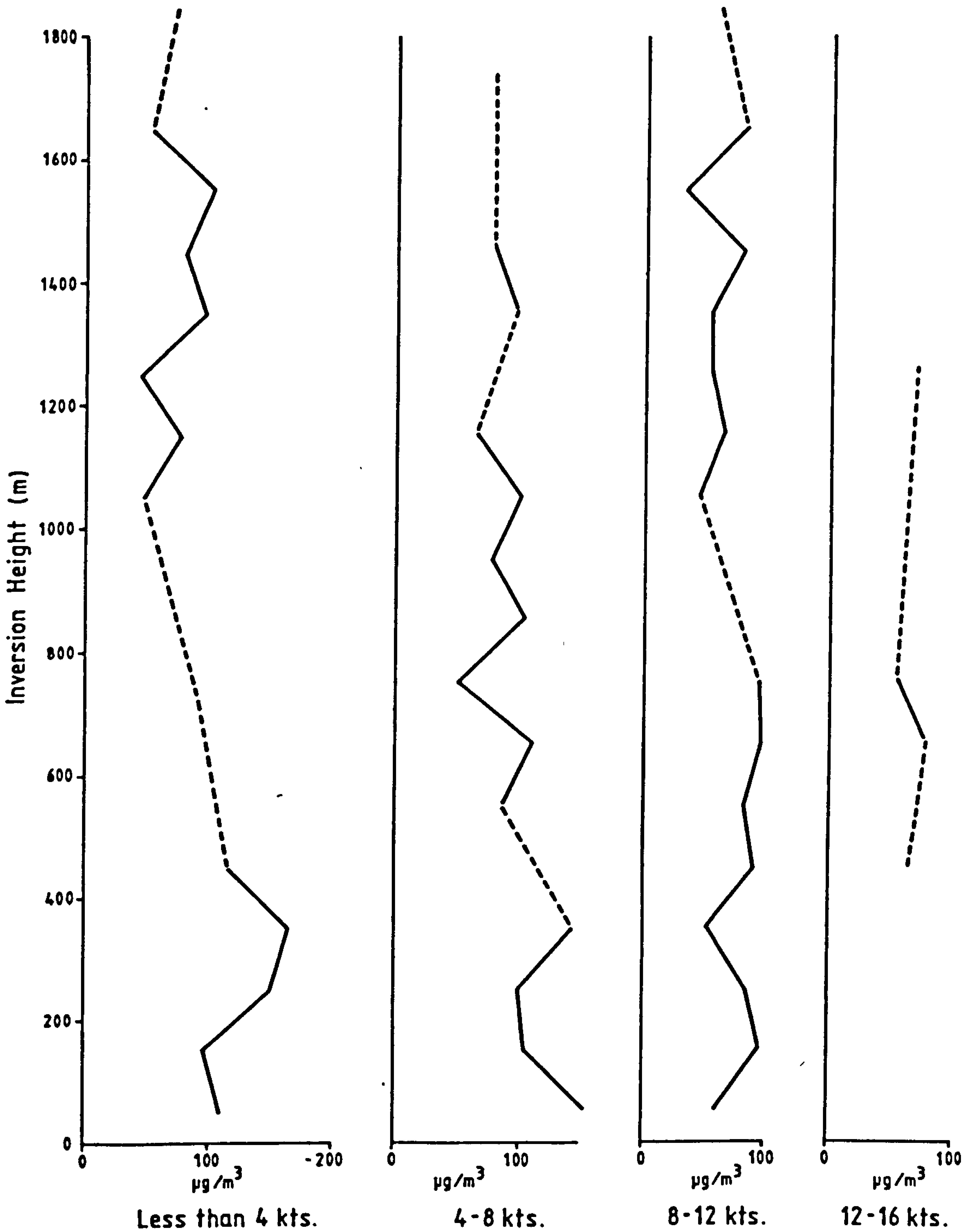
Such circumstances might be expected to be most common in summer when radiation output from the ground is at its maximum and accordingly the thermal boundary layer development would be expected to be near its maximum altitudinal extent. However, when the data was examined on a daily basis this was not found to be the case. High level inversions were found to be just as likely to be associated with above average concentrations in winter as in summer. Thus, while a small fraction of the occurrences contributing to these categories may reflect fumigation below high level inversions, some other cause seems likely for the vast majority of the cases. The most likely explanation is that on these occasions some lower level of trapping may have been operative in the Glasgow Basin and not apparent on the radiosonde. As was seen in the previous section, the thermograph data tends to support, if rather tentatively, this contention and thus these high level peaks may be attributable to lower level trapping than Fig. 10.2 suggests.

Inversions tend to rise as wind velocity increases. This is apparent throughout the upper air plot for the Shanwell soundings. It is especially true of surface based inversions which often become detached from ground level on the noon radiosonde ascent, producing a 'lifted' inversion which may either dissipate or reappear at the surface on the midnight sounding. Inversion heights and wind velocity are thus closely correlated phenomena.

Bearing this in mind the mixing height data can nevertheless be grouped according to various wind speeds. This is done for the easterly sector (030°-090°) in Fig. 10.3. From this it would seem that higher inversions provide the most effective traps when wind velocities are greater. With low wind velocities the most effective trapping takes place with inversions up to about 300 metres. This seems to be due to the 'ponding' of pollutants by the Renfrew Heights and Gleniffer Braes, an effect similar to that noted earlier. With higher wind speeds, however, it is inversions based first at about 500 metres, the level appropriate to the Campsies, and then at about 700 metres, the level of the Highlands and Southern Uplands themselves, which appear to be most effective. The 700 metre level is indeed the only noticeable deviation on the highest wind velocity category. This is related to the ability of the relief at this level to canalise these winds, and channel effluent into the Basin from distant sources in the Forth Valley. Indeed it will be shown in Chapter 11 that this mechanism is particularly significant in terms of maximising the effect of the Longannet plume at stations west of Glasgow.

Thus it is apparent that the interaction of relief considerations and the existence of temperature inversions at certain critical heights is a highly important control on the dispersal of pollutants within the air shed. Under certain circumstances this interaction enhances ground level concentrations both by restricting the dispersal of pollutants emitted within the area, and also by being instrumental in encouraging pollution from outside to be imported in a relatively undispersed state. While the diversity of relief characteristics of the area makes these complicated relationships to unravel, they nevertheless must be understood, or at least appreciated, if the impact of new polluting industry is to be accurately predicted.

Inversions, SO_2, with Various Wind Velocities from 030°–090°



(i) Only Averages based on 4 or more values plotted
(ii) Midnight Data 1971-77
(iii) Pollution data from Linwood

Fig. 10.3 Inversions, SO_2, with Various Wind Velocities from 030°–090°

CHAPTER 11

INVERSIONS AND EASTERLY WINDS

11.1 The Basis of Enhanced Pollution with Easterly Winds

Previous sections have suggested that significantly higher concentrations of sulphur dioxide are observed with winds from an easterly direction as opposed to winds from other sectors. To test the validity of this some form of statistical analysis is appropriate.

Initially the null hypothesis is assumed. This states that there is no significant difference between concentrations observed on easterly and other winds. A month's data was then selected at random from the seventy-two months of the record. Daily values for this month (May, 1977) were classifield into two groups according to the average mean vector wind direction for the day. Where this lay in the range 000^{o}-180^{o} the day was categorised as one with an easterly type wind regime. The two groups thus created were then ranked and the Mann-Whitney U test was applied. A value less than the critical value at the 99.5% confidence level was obtained suggesting that the null hypothesis could be rejected. Significantly higher concentrations are therefore observed with easterly winds.

It might now be argued that this difference is itself primarily due to an increased incidence of stronger winds in non-easterly sectors, for the particular month in question. Such a hypothesis was, however, easily disproved using a chi-squared test on the wind direction and speed data. No significant difference was found for the sample month between velocities observed with easterly and other wind directions. Extreme value analysis for the whole of the study period might well have suggested the opposite conclusion, with the incidence of westerly gales, for example, considerably greater than their easterly counterparts. Nevertheless, since a significant difference in concentrations exists on the basis of the data selected this suggests that a contrast in source intensities exists between east and west.

Before considering in detail which sources are responsible for this discrepancy it is worth repeating four important conclusions reached already which directly involve the question of pollution loading on easterly winds.

(i) Easterly winds are characterised by generally stable conditions, often in association with an anticyclone nearby. A subsidence inversion is frequently in existence in the lower 2,000 metres of the atmosphere.

(ii) The sector 045°-074° is particularly polluted and corresponds in bearing to the Cumbernauld Gap, the principal low level corridor between the Forth and Clyde Basins.

(iii) Double maxima were observed on the concentration versus windspeed table for this direction (see Table 7.6) which were most marked under stable nocturnal conditions.

(iv) Critical inversion heights were apparent which appeared to canalise pollution from more distant sources.

Substantial evidence thus appears to exist which when interpreted might suggest that under specific meteorological circumstances large scale transport of pollution from a source or sources beyond the Clyde Basin may occur and may be funnelled through the Cumbernauld Gap beneath inversion lids, especially those occurring at about 450 metres or 700 metres. That such phenomena can be detected at Linwood is remarkable in view of not only the considerable travel distance involved, over 50 kilometres, but also the passage of pollutants over a city of one million people and considerable intervening emissions of SO_2 from various industrial sources. Such a transport capability would appear to be fulfilled only by a source of considerable intensity, regularity and buoyancy, characteristics which prompt further examination of the major sources in the Forth Valley in the sector 045°-074°.

11.2 Potential Major Sources of SO_2 in the Forth Valley

A straight line of a bearing 070° from the Linwood monitor passes neatly through the valley occupied by the upper Kelvin and the Forth-Clyde canal which is itself aligned along this bearing. After breaching the watershed at about 60 metres O.D. in the vicinity of the Cumbernauld Gap the line continues through the lower Carron valley eventually reaching the Forth at a point midway between Kincardine and Grangemouth, and directly opposite Longannet Point on the Fife shore. The importance of this trajectory cannot be understated, since the three locations mentioned account for three of the most significant sources of SO_2 in Central Scotland.

The rocky outcrop at Longannet Point was a suitable site for what was, at the time of construction in 1971, Scotland's largest power station, representing more than half of the generating capacity of the South of Scotland Electricity Board. Built during the era of relatively cheap oil supplies, the choice of coal as the fuel to be used reflected political rather than economic considerations. Longannet was to be to the depressed Fife Coalfields what Cockenzie had been to their Lothian counterparts, a market which enabled more painless contraction of the industry. Indeed half of the coal used is brought to the surface within the boundaries of the station through an inclined shaft leading to the modernized Longannet Mine complex. Further supplies are obtained from local pits by a greatly extended railway network connecting them with the station. Five million tonnes of coal are consumed per annum to drive the four identical 600 MW generating units. The two most important features of the station from the air pollution point of view, however, are the emission characteristics and the extent to which the station is active.

Prior to the construction of Inverkip Power Station

Longannet's 183 metre chimney was the tallest concrete structure in Scotland, consisting of four flues surrounded by a 174 metres high concrete windshield. The centre of the chimney has space for a lift shaft and stairway. The station first achieved its full output of 2,400 MW in January 1973 and since then it has consistently provided the bulk of all electricity generated in Scotland. Between April 1973 and April 1977 the station generated some 43,400 million units of electricity, representing a load factor over this period of 51.6%. This appears somewhat low for a baseload station and probably reflects a marked seasonal demand for electricity supplies as well as interruptions due to labour disputes, coal supply difficulties and equipment failures within the station. More realistic values perhaps are given by the S.S.E.B. (1973) when they suggest that all four generating sets are normally in action over the three winter months of December, January and February. A load factor of 71.1% was claimed for one such period equivalent to a power generation rate of over 1700 MW.

Kincardine Power Station is a much smaller, older coal-fired station located two kilometres upstream of Longannet. Indeed Longannet was partially constructed on a site reclaimed from the Forth by boiler ash from Kincardine. Generation capacity, by modern standards, is only moderate with the five generators producing a total output of 715 MW, most of which goes to meet demand from the Edinburgh area. As with its counterpart on the other side of the city, Cockenzie, output into the atmosphere is by a two chimney system. Those at Kincardine are of moderate height at 138 metres suggesting that plume rise will be much below the Longannet value although under certain circumstances the two plumes may have become entrained together beneath the inversion lid. Reference back, however, to Table 7.2 reveals that Kincardine, following the closures of older plant already described, is now virtually at the base of the efficiency league table of costs. The station has been on a 'care and maintenance basis' since 1978 operating mostly when labour disputes or mechanical trouble afflicts generating capacity elsewhere.

Grangemouth, on the south bank of the Forth is now a major British oil refinery following its linkage to B.P.'s Forties Field. Previously it received crude oil through a pipeline from the deep water terminal in Loch Long, at Finnart. About 8.5 million tonnes of oil per annum are handled, equivalent to some 6% of the total U.K. refinery throughput in 1976. It is normally assumed that some 5% of the total annual throughput of crude oil will be used for power purposes within the refinery although for Grangemouth this figure may be higher. This is often a mixture of low sulphur gas and high sulphur oil which is equivalent to a sulphur content of about 1.5% (Keddie and Williams, 1974). For Grangemouth this is likely to be an overestimate however, in view of the low sulphur content of North Sea oil and gas. The sulphur dioxide output is therefore not likely to exceed 0.40 kg./sec although this is itself a considerable quantity in comparison to for example Braehead's 0.77 kg./sec (67 tonnes/day) SO_2 output.

Close to the refinery the I.C.I. petrochemical plant is also a significant source of SO_2. The effect of these emissions, however, is likely to be felt most in the area immediately downwind, particularly from 2-10 kms. Effective emission heights are fairly low and good dispersal seems likely before funnelling in the Cumbernauld Gap would occur. Under the calm conditions necessary to achieve a sufficient plume rise to produce a maximum in the range 20-50 kilometres extremely light winds would hinder transport to the point at which other removal processes would become more dominant.

As part of an emission inventory compiled for Warren Spring's Forth Valley Survey, Keddie et al (1978) examined these three major sources and concluded that they account for 89% of total SO_2 emissions in the Forth Valley. No values were published, but it is possible to calculate emissions from Longannet according to the following formula:

$$E_{(SO_2)} = 2 \times S \times (1-R) \times C_f \times K$$

where

$E_{(SO_2)}$ = Annual SO_2 emission (kg/yr).

S = % Sulphur content of fuel (0.7% for Scottish coal).

R = Proportion of sulphur retained in the ash, and not emitted (10% for coal).

C_f = Annual coal consumption.

K = Constant (1,016) to convert the units of tons/yr to kg./yr.

Annual coal consumption for Longannet for the financial year April 1978 - March 1979 was 5,164,288 tonnes (5,081,324 tons), (Wallace, 1979), representing a load factor of 56.4%. On this basis total SO_2 emissions from the station during the year were 65,049,076 kg. or some 65,049 tonnes. This figure must be seen in relation to Ollswang's estimate of 463,000 tonnes for the whole of West Central Scotland for 1969/70 (see Chapter 3) and also Keddie and Williams' (1974) estimate for Inverkip at full capacity of 230,000 tonnes.

Clearly Longannet represents the major single source of SO_2 in Scotland at present. The emission characteristics furthermore suggest that the plume may be hot enough and buoyant to travel a considerable distance downwind before dispersal occurs. It is thus appropriate to examine further the observed concentrations in order to ascertain the extent to which any such effect is apparent.

11.3 Measuring the Effect of the Forth Estuary Sources

The difficulties of predicting the behaviour of a pollution plume which is subjected to atmospheric dispersal have been outlined by Forsdyke (1970) who claimed that 'the problem of turbulent motion is the most difficult of those which arise in fluid dynamics. A complete mathematical solution of the problem of pollutant distribution is, therefore, not possible.' Most controversy centres on attempts to predict plume rise since this is central to the argument between advocates of high stack dispersal policies and their opponents. The most familiar formulae are those of the Memorandum on Chimney Heights (Ministry of Housing and Local Government, 1967), of CONCAWE (Brummage, 1968) of Slade (1968), or the more complicated complete application of the Sutton formulae used by Lucas (1975). Regardless of which formula is chosen, however, satisfactory results are not consistently produced (Open University, 1975). It would appear that if the formulae are checked on the basis of visual observations then on individual occasions discrepancies of up to 50% are apparent. This error is further enhanced by up to 40% where irregular terrain is in evidence. Such a range of error has serious implications for calculations involving ground level concentrations, a situation which prompted Pasquill (1971) to remark that "this is a subject with a very wide and scattered literature, and with more formulae and dispute than any other aspect of our present subject."

Plume rise is utilised to calculate downwind concentrations by the Gaussian Plume Model, the primary method in widespread use. Pasquill (1971), Smith (1973), and Turner (1970) have outlined the general usefulness of the model while Ragland (1976) has concentrated on deriving the conditions under which the worst case concentrations will be observed.

For a coning plume, when the ratio of the vertical to lateral dispersion coefficient does not depend on distance downwind, the ground level concentration, C, along the centre of the plume is given by :

$$C = \frac{Q}{\pi U \sigma_y \sigma_z} \exp\left[-\frac{H^2}{2\sigma_z^2}\right] \qquad (1)$$

where Q is the emission rate, U the windspeed at stack height, H the effective height of the emissions and σ_y and σ_z are the lateral and vertical dispersion coefficients respectively.

Since σ_y and σ_z functions of downwind distance x and atmospheric stability it is convenient to let

$\sigma_z = ax^b$ and $\sigma_y = cx^d$

where a, b, c and d are dispersion coefficients based on the stability category in question.

Substituting into the original formula gives:

$$C = \frac{Q}{\pi U a c x^{(b+d)}} \exp\left[-\frac{H^2}{2a^2x^{2b}}\right] \qquad (2)$$

The maximum concentration from such a plume will occur when the rate of change of concentration with downwind distance is zero. Differentiating for $\frac{dc}{dx} = 0$ gives:

$$x_{max} = \left[\frac{bH^2}{-a^2(b+d)}\right]^{\frac{1}{2b}} \qquad (3)$$

Prior to assessing the effect of the major sources of SO_2 in the Forth Valley on the Linwood concentration data two problems arise. The first concerns the nature of the dispersion environment on easterly winds, whether it may be characterised as unstable, slightly stable or stable. This determines the particular set of dispersion coefficients to be chosen. Ragland's work indicates that the distance of maximum concentration is ten times further downwind in slightly stable conditions than it is in unstable conditions for a stack height of 200 metres. Obviously the choice of dispersal co-efficients is of central importance and merits examination of the stability data described in Chapter 6.

For all wind speeds the stability categories calculated by Stabwind (see Chapter 4) were analysed where directional bearings fell in the category 045^{o}-074^{o}. Table 11.1 shows the distribution of occurrences in each category, with the corresponding values for all the wind observations in the six years. At first sight the two distributions appear similar with close matching in terms of rankings. However , a chi-square test (Table 11.2) suggests that a significant difference does exist between the pattern of stability categories observed on easterly winds and the overall wind regime.

The obvious question arising is whether or not the distribution with easterly winds is characterised by a tendency for a greater occurrence of stable conditions, i.e. do stable conditions occur more frequently with easterly wind directions than with overall wind directions? On examination of the observed minus expected cells of Table 11.2 easterlies would appear to be poorly represented in the unstable categories 1 and 2. By contrast however, they appear over represented in the neutral and slightly stable categories 3, 4 and 5. Furthermore this over representation appears highly significant, at the 0.001 level for category 3 and 0.01 level for category 5 (see notes (i) and (ii)). In the stable categories 6 and 7 a slight under representation is apparent, though this is not significant at either of the two levels above. Such a situation of under representation in both unstable and stable extremes makes conclusions impossible to draw without considering other factors.

It is suggested here that the increased tendency for stability evident from consideration of categories 1-5 is valid, but that the diminished frequency of stable

Table 11.1 Stability Categories on Easterly Winds

Category	045-074°		All Winds		Approximate Pasquill Stability Categories
	No.	%	No.	%	
1	18	1.5	183	2.3	A
2	119	9.9	977	12.5	B
3	280	23.4	1428	18.3	C
4	538	45.0	3752	48.0	D
5	140	11.7	733	9.4	} E
6	87	7.3	582	7.4	} E / } F
7	14	1.2	166	2.1	} F
Σ	1196	100.0	7821	100.0	

Table 11.2 Chi Squared Test - Stability Distribution

Stability Categories	Observed O	Expected E	O-E	$(O-E)^2$	$\frac{(O-E)^2}{E}$
1	18	28	-10	100	3.57
2	119	149	-30	900	6.04
3	280	219	61	3721	16.99 (i)
4	538	574	-36	1296	2.26
5	140	112	28	784	7.00 (ii)
6	87	88	- 1	1	0.01
7	14	25	-11	121	4.84

(i) Significant at 0.001 Level) With 1 degree of freedom
(ii) Significant at 0.01 Level)

$$X^2 = \sum \frac{(O-E)^2}{E} = 40.7 \qquad df = 6$$

Critical Value (0.001) = 22.5

∴ Stability Categories with Winds 045-074° are significantly different from those with the overall wind regime.

occurrences is a misleading value reflecting local factors.

It must be noted at the outset that these stability estimates are based on surface observations of windspeed and cloud cover at Glasgow Airport, to be west of the city. This being the case, the stability data may on occasion be unrepresentative either of conditions in the Forth Estuary Area, or along the intervening area between sources in this area and the Linwood monitor. For example it could be hypothesised that under an easterly drift less cloud may be apparent to the west of the corridor than in the vicinity of the Forth Estuary. This being so conditions at Glasgow could be expected to suggest a slightly more stable regime than might have been observed at Turnhouse for example. Other influences might act in the opposite manner. In particular, the location of Glasgow Airport means that the easterlies observed there have had to traverse the urban mass of the city. Two consequences of this might be expected to induce instability. Firstly, of course, the surface roughness of the built-up area results in increased turbulence being injected into the air flow. But secondly, the effect of the city's heat island would be considerable under certain circumstances, resulting in low level heating of the airflow passing over the city. Such an effect would be most noticeable when the heat island was most enhanced. This was noted by Hartley (1977) in his study of Glasgow's heat island to occur under light wind conditions with stable conditions prevailing.

Thus it is fairly clear that stability estimates from Abbotsinch can only hint at stability conditions in the vicinity of the source or along the corridor which the plume must traverse before reaching Linwood. Conflicting influences may render the stability estimates at Linwood either more or less stable than was the case further east. Despite this, however, the under representation of easterlies in category 7 suggests that the influences inducing instability are dominant. This being so it can be suggested that easterlies are characterised by more stable conditions and that the passage of a plume from the Forth Estuary through the Cumbernauld Gap is more likely to occur with a stable, stratified air flow, than with an unstable one. Further data, from locations to the east of Glasgow might well substantiate this assertion. Note was also taken in Chapter 7 that the double maxima apparent with winds from the east were only observed on nocturnal wind observations. It was suggested then, and can be reiterated here, that such a phenomenon is explicable only in terms of a more stratified air flow in the more stable nocturnal atmosphere.

Bearing in mind the deficiencies in the stability data mentioned above, the dispersion co-efficients utilised with north easterly and easterly winds were those corresponding to slightly stable conditions. Those developed by the Tennessee Valley Authority (Carpenter, 1971) were recommended by Ragland (1976) as being the most appropriate for tall stacks, the category into which Longannet (183 metres) falls. The constricting effect of the Cumbernauld Gap on the lateral dispersion of the plume might, also be considered to have a similar effect to increased stability in suppressing dispersion and would further justify the choice of dispersion co-efficients made.

The effective plume rise in terms of locating the point of maximum ground level concentration to the west of Glasgow can now be calculated by substitution into formula (3) thus:

$$\therefore \quad 55000 = \left[\frac{0.5\ H^2}{1.42^2 \times 1.19} \right]^{\frac{1}{2 \times 0.5}}$$

$$\therefore H^2 = 263946.76$$

$$H = 514 \text{ metres}$$

But since $H = h_s + \Delta h$

where $h_s = 183\text{m}$

$$\Delta h = 331 \text{ metres}$$

Thus a plume rise of 331 metres at Longannet will, under a north easterly wind produce its peak ground level concentration in the vicinity of Glasgow. To find the appropriate critical wind velocity under which this is achieved it is necessary to substitute back into the Concawe formula:

$$\Delta h = 86\ Q^{\frac{1}{2}}\ u^{-3/4} \qquad \text{—(4)}$$

where Q is the emission rate in megawatts
and u is the windspeed in metres per second.

Estimating the value of Q, for Longannet is the second problem and the major source of error in the whole process, despite the existence of the performance figures mentioned earlier. A useful source of reference however was found in Keddie and William's (1974) calculations on the impact of Inverkip Power Station. For each of the three 660 MW generators they allowed a heat output through the stack of 74MW, making 222 MW if the station was operating at its 1,980 MW capacity. A comparable estimate for Longannet operating at capacity would therefore be Q = 269 MW. During the cold spells in winter which would accompany north easterly winds it is likely that electricity demand would be fairly high and capacity, or near capacity, operation of the station is probable. In their Annual Report for 1973 the S.S.E.B. (1973) claim that over the winter period as a whole a load factor of 71.1% existed, meaning that for long spells the station was probably operating at full capacity.

Substituting into formula (4) the value of u, the critical wind speed, can be found.

$$U^{3/4} = \frac{86\ (269)^{\frac{1}{2}}}{331}$$

$$= 4.26$$

$$\therefore\ U = 6.9 \text{ metres/sec} \gtrsim 7 \text{ metres/sec}$$

$$= \sim 14 \text{ knots}$$

This calculation therefore suggests that with a north east wind of about 14 knots, at the stack top, and Longannet working to full capacity, peak concentration will occur on the western edge of the Clydeside conurbation, a conclusion with widespread implications for pollution control policies within the Glasgow Basin.

The magnitude of such ground level concentrations can also be calculated by substitution into equation (1). The only unknown is now Q, the emission rate in μg/sec for Longannet at full power. This can be deduced as follows:

Annual Coal Consumption 1978/79	=	5,164,288 tonnes
Load Factor for corresponding period	=	56.4%
Annual Coal Consumption at 100% load factor	=	9,156,539 tonnes
SO_2 Emissions at 100% load factor (see section 11.2)	=	115,335 tonnes
SO_2 Emission rate at full capacity	=	3.6×10^9 ug/sec

Substituting into (1) now gives:

$$C = \frac{3.6 \times 10^9}{3.14 \times 7 \times 1026.08 \times 333} \exp \left[- \frac{514^2}{2 \times 333^2} \right]$$

$$= 479.3 \exp \left[-1.19 \right]$$

$$C = 144 \ \mu g/m^3$$

Examination of the data partially vindicates the contentions made earlier. In particular the wind speed/concentration data for the appropriate sector provides evidence that Longannet pollution is reaching the monitor with moderate easterly winds. It was noted in Chapter 7 (Table 7.5 and 7.6) that for the bearing 045^o-074^o double maxima exist which have been shown to relate to nocturnal airflow through the Cumbernauld Gap. The secondary peak occurs with windspeeds of 13-14 knots, which, though they relate to surface and not stack top windspeeds, are sufficiently close to the predicted speed calculated earlier to suggest that this is direct evidence of the Longannet plume being detected to the west of Glasgow. Of course some of this secondary peak may relate to contributions from Braehead in the past, and conceivably Kincardine and the Grangemouth refinery, though further analysis would be necessary to confirm this.

In turning to consider the situation where the plume is trapped below an inversion at height Z the concentration along the plume centre line has been derived by Ragland (1976) as being:

$$C_t = \frac{Q}{\pi \sigma_y \sigma_z U} \sum_{n=-\infty}^{\infty} \exp\left[-\frac{(H-2n\, Z_m)^2}{2\sigma_z^2}\right]$$

The worst case will occur when the plume rise is just up to the inversion layer (Z_m), (Kumar and Djurfors, 1977), hence:

$$C_t = \frac{2Q}{\pi \sigma_Y \sigma_z U} \sum_{n=1}^{\infty} \exp\left[-\frac{(2n-1)^2 Z_m^2}{2\sigma_z^2}\right]$$

At the point of maximum concentration the rate of change of concentration with distance is zero, so that:

$\frac{d C_t}{d x} = 0$ thus by taking a few terms of the series it can be demonstrated that:

$\left(\frac{H}{\sigma_z}\right)^2 \approx \frac{b + d}{b}$ at the distance of maximum concentration.

This result could also have been achieved from further simplification of equation (3) for the coning case. Since typically (b + d)/d varies from 1.5 to 3 near the point of maximum concentration it is sufficient to carry only the first term of the series:

$$\therefore C_{t_{worst}} = \frac{2Q}{\pi \sigma_y \sigma_z U} \exp\left(-\frac{Z_m^2}{2\sigma_z^2}\right)$$

But as Kumar and Djurfors (1977) noted, at the worst concentration the height of the inversion and the effective chimney height are equal, $Z_m = H$. This means that this result is exactly twice that observed in the absence of an inversion.

Thus it can be concluded that the effect of an inversion is to double the maximum concentration, this occurring when the inversion height equals the effective chimney height. The critical wind speed and the position of the maximum concentration are unaffected by the existence of an inversion except when it occurs below the height of the stack or low enough for the entire plume to penetrate it.

The practical rather than hypothetical effects of inversions are demonstrated in Fig. 10.3, and at this point it is appropriate to examine this diagram in the light of what has been suggested above.

The relevant category for wind speed is probably 8-12 kts. This would contain those categories with a stack height wind of about 14 knots. It can be seen from the data in this category that three maxima appear to exist with inversions below 1,000 metres. The highest one occurs at about 650-700 metres with corresponding SO_2 concentrations of about 100 $\mu g/m^3$. It is suggested that this represents the trapping of the Longannet plume when the station is at full power. As was earlier demonstrated, under the critical wind speed condition a plume rise of 331 metres would occur making an effective source height of 512 metres whose maximum concentration would occur to the west of Glasgow. An inversion at plume rise height would maximise this concentration, and this is what appears to be demonstrated on the diagram. Furthermore it is also interesting to remark that with inversions above 1,000 metres, (non effective as trapping inversions), a concentration value in the region of 50 $\mu g/m^3$ seems to be the norm. With the inversion close to effective source height (maximum enhancement), concentrations close to 100 $\mu g/m^3$ are observed. The maximum effect of an inversion is thus a doubling of ground level concentrations at the point of maximum concentration.

For the other two maxima apparent, the lower one below 200 metres, would seem to be due to local sources. The maximum at about 450 metres is, however, less easy to explain. It does not seem to be connected with the one at 350 metres on the lower windspeed categories and so may well represent a discrete source. The Concawe formula, equation (4) could be utilised were the stack height of such a source known. However if a stack height of 183 metres is utilised, the formula suggests that a source of strength Q = 178 MW is responsible. Such a criterion would clearly be met by Longannet working at about 66% capacity. Thus the maxima may reflect Longannet pollution with a less buoyant plume.

In an age of rapidly escalating energy costs power stations are under great pressure to perform at high efficiency levels for sustained periods. Power station managers must inevitably be aware that heat output through the stack is money lost, and appears in the annual accounts as a reduction in operating efficiency. There must therefore be a strong temptation to reduce stack heat output on occasion resulting in less buoyant plumes than projectedby the architect. The maximum at about 450 metres could thus reflect Longannet operating with a less buoyant plume. Additional data between 400 metres and 700 metres on the lower windspeed categories might well have confirmed this hypothesis.

Although in absolute terms the effect of an inversion is felt most at the point of maximum concentration, in relative terms it is even more significant with increasing downwind distance. The ratio between trapping and coning concentrations thus increases from two to one to values many times this further downwind.

In conclusion, it is important to try and reconcile these arguments based on the trapping of pollutants from a particular source with the conclusions reached earlier in this study. In particular the importance of trapping inversions at 450 metres and 700 metres is highly significant. It will be remembered from Chapter 10 that inversions based at 400 metres and 700 metres were most effective trapping agents for all wind directions because of their relationship to important erosion surfaces close to these heights. What has now been demonstrated is that, in addition to critical inversion heights related to relief influences, in addition to critical wind bearings related to relief funnelling, there exists (as far as the Glasgow Basin is concerned) significant inversion heights in relation to source strength for the principal source of SO_2 in Scotland. The proximity of 450 metres and 400 metres and the coincidence of 700 metres for both sets of influences emphasises that both may on occasion reinforce each other in producing enhanced ground level concentrations in the Glasgow Basin. The evidence for this reinforcement can be seen in Table 11.3.

The role of inversions in the free air has thus been shown to be a most important control on pollution concentrations many kilometres from the source. Theoretical predictions concerning the dispersal of high level effluent from the Forth Valley have been confirmed by observations which demonstrate the marked effect of inversions at plume rise height acting in conjunction with relief influences. The capability for long distance transport of pollution beneath an inversion lid is indirectly inferred as is the possibility of fumigation in previously unpolluted areas. These considerations seem to lie behind the U.S. Environmental Protection Agency's reluctance to accept tall chimneys in its control policies. On the evidence presented here tall chimneys do appear in fact to 'spread pollution further afield' and partially explain the view gaining ground within all the countries of the E.E.C. that "constant emission reduction techniques such as flue gas desulphurisation are far superior to dispersion techniques" (U.S. E.P.A., 1973).

Table 11.3 A Simplifed Representation of SO_2 Concentrations Associated with a Combination of Circumstances

	All Wind Bearings	030°-090° 8 - 12 kts.
Overall Concentration	53	71
All Inversions < 4,000 m	53	72
Inversion at 400 m	75 (i)	75
Inversion at 450 m	58	92 (ii)
Inversion at 700 m	65 (i)	96 (iii)

(i) Enhancement primarily due to erosion surface influences

(ii) Enhancement due to maximisation of pollution from Longannet

(iii) Combination of (i) and (ii).

CHAPTER 12

INVERSION PERSISTENCY

12.1 Air Pollution Potential

Once established, a temperature inversion is an intrinsically stable phenomenon, requiring a considerable energy input, thermal or mechanical in origin, to destroy it. Scorer (1968) emphasised this when he calculated that about 10^{10} joules would be needed to mix the air over one square kilometre confined below an inversion of $5^{o}C$ at 500 metres into twice its depth. This implies an element of persistence which is an important consideration in forecasting high pollution episodes with a view to minimising their adverse effects.

Since 1960 routine forecasts of air pollution potential have been issued for most parts of the United States (Bach, 1972). When these bureaux forecast a potential in excess of 1000 $\mu g/m^3$ some authorities have the legal authority to force major polluters to cut their emissions, or even shut down entirely, during the period of the alert. New York and Philadelphia, for example have the authority to make power stations and industries switch to low sulphur fuel and impose restrictions on the mobility of the private motorist during such periods. A similar system exists in the Ruhr in Western Germany.

Two criteria on which the forecasts are principally based are the mixing height and wind speed. Those areas, therefore, with the most frequent alerts correspond closely with those areas having the most frequent temperature inversions. These in turn correspond to areas with a high frequency of stagnating anticyclones, in the case of the United States, areas such as California and Appalachia. In these areas inversion frequency, and also inversion persistence, is high and the direct link this has with air pollution episodes can be clearly shown. In applying these ideas to West Central Scotland, however, the picture must not be over simplified, and the persistency factor must also be seen in relation to the critical mixing heights identified in Chapter 10.

12.2 Previous Work in Inversion Persistence

Despite its obvious relevance to air pollution dispersal relatively little work has been done in the field of inversion persistence. More emphasis on forecasting occurrence is apparent, as for example, in the work of Shellard and Hay (1961). On the basis of one year's radiosonde data from two Atlantic weather ships the relationships between the occurrences of both frontal and subsidence inversions and various synoptic features were used to derive rules for the prediction of inversion occasions. Though 90 per cent successful for non-frontal cases the technique found only limited application since the information needed most for air pollution studies relates to inversion height and duration as described above, rather than prediction of a likely occurrence only.

Hardy (1973) compiled an exhaustive tabulation of inversions at Cardington based on ten years' data obtained from a tethered balloon. Unfortunately, as the author readily admits, limitations imposed by the maximum height of ascent (1,200m) and by instrumentational problems make these data rather biased. Many ascents were either cancelled or curtailed during strong winds or when a risk of lightning or icing was present. Cancellations or curtailments due to wind speed were most common during daytime close to the surface, especially around midday. Above about 300 metres nocturnal winds were primarily responsible. Lightning risk was highest during daylight hours while icing most affected the ascents made at 00.00h and 06.00h. Due to these problems a large number of scheduled ascents were not commenced or were curtailed before reaching 1,200 metres. Complete data up to this altitude was therefore obtained for only 28.5 per cent of the study period. Despite this inversions were found to be most frequent and persistent during winter and autumn. More marked seasonal differences were observed at Cardington than at Long Kesh (see below) undoubtedly reflecting the inland location of the former as well as the limitations of a tethered balloon sampling only the lower levels of the atmosphere most affected by ground influences.

Discrimination between lower radiation and higher subsidence inversions could be made by Voloshin (1973) using radiosonde data for Kiev and Kharkov. Winter and autumn maxima were also noted despite the obvious climatic contrasts with the British case. Table 12.1 shows that 4,738 inversion occurrences were observed during the four years of which 26 per cent were below 250 metres and lasted for less than a day. These are obviously surface features and indicate the suitability of the continental Ukrainian climate for radiation inversions. Indeed many of the occurrences in the 0.25-1 km range may also be attributed to deep radiation type inversions. Surface inversions are not persistent and are generally dissipated by noon on the day following. Even in winter they last only three to four hours longer than their summer counterparts. Of the persistent inversions, 109 occasions which lasted for over two days occurred (Table 12.2) enabling some degree of comparability with the Long Kesh data.

Table 12.1 Inversion Occurrences at Kiev 1956-60

Duration (Hours)	Altitude (Km)					
	0-0.1	0.1-0.25	0.25-0.50	0.50-1.0	1.0-1.15	1.5-2.0
less than 12	614	616	524	363	344	426
12-24	259	373	244	174	208	221
24-48	22	27	49	61	70	34
48-72	1	4	12	24	12	3
72-96		3	3	14	7	1
96-120			3	6	2	
120-168			4	4	2	
168-216				3		
over 216				1		

Table 12.2 Persistent Inversions at Kiev 1956-60

Duration (days)	No.
2-3	56
3-5	39
5-7	10
7-9	3
9-	1

12.3 Long Kesh Inversion Persistence

One drawback in Voloshin's results is that only one per cent of inversions seem to persist over three days, a seemingly unlikely situation in such a continental climatic regime. This may be a consequence of the selection criteria which may have resulted in a fragmentation of episodes into smaller occurrences at the various heights. Inversions rise and fall, coalesce and divide, disappear and reappear often without any obvious cause, resulting in great difficulties for anyone seeking to explain their behaviour. The relatively recent development of acoustic radar sensing has, however, proven to be extremely useful in this respect in monitoring short term changes in both stability and inversion behaviour in the lower atmosphere.

Acoustic energy propagating upwards through the atmosphere is reflected by turbulent fluctuations of temperature and wind velocity. By analysing the returned echo the monostatic sounder gives an indication of the changes occurring, in both lapse rate and dynamic stability, along the path of the transmitted pulse. This produces a record with a considerable contrast range which can be closely related to the temperature structure of the air through which the pulse passed. The principal advantage of acoustic sounding is its capability of providing a virtually continuous record. In contrast, the radiosonde provides only a twice daily sample and is subject to systematic errors due to a time lag in the response of its pressure and temperature sensors (Wyckoff, 1973).

Despite these drawbacks, however, the data source for this part of the study was based on the twice daily (00h and 12h) radiosonde ascents at Long Kesh, Northern Ireland. In part this choice reflected the absence of an acoustic record over a sufficiently long period. However, the practical difficulties, involved in using acoustic data were also considered an obstacle to achieving results comparable with research elsewhere. In particular, the interpretation of such a record would have involved a considerable degree of subjectivity the consistency of which would have been difficult to maintain over a long time period.

The failure of the radiosonde to provide a continuous spectrum of data necessitates making the assumption that an inversion persists in the intervening period between successive ascents where it is observed. Since this is not necessarily the case over a twelve hour period then this implicit assumption must be seen as a weakness in the study. However examination of the intermediate wind observations made at 06h and 18h suggested that, for the vast majority of cases, a wind shear at similar altitudes existed, indicative of the probable continuance of inversion conditions. This would seem to suggest that the assumption of persistence between ascents is justified and does not preclude the derivation of valid results from this source.

Much of the previous work outlined above involved a method analysis based on the occurrence or otherwise of inversions within fixed altitudinal bands. Where an inversion oscillated across these boundaries, moving from one band into another, fragmentation of the episode resulted. A method avoiding this was sought which would enable an inversion to be followed in its path through the various atmospheric levels and a truer picture of inversion persistence to be obtained. It was found that this objective was best achieved when the following simplifications were applied to the data.

(i) Only the lower 4,000 metres of the atmosphere were considered.

(ii) Surface inversions were ignored except where they formed part of another inversion period with a mean level in the free air.

(iii) When more than one inversion existed only the lowest one was considered.

(iv) Inversions were allowed to vary in height (mid height) by up to 1,000 metres during successive observations and still remain part of the same episode.

(v) Allocation into height categories was on the basis of the mean altitude (of the mid heights) during the whole of the episode.

A computer programme incorporating these restrictions was written which produced a series of inversion episodes over the six year period. The inversion 'tracking' qualities of this approach represents a particularly valuable innovation in this field, characterising each inversion episode in terms of duration and its mean altitude. Aggregation of the episodes produced by this novel technique yielded a contingency table from which important conclusions regarding the nature and effect of inversions could be deduced. Table 12.3 summarises the results obtained. At all altitudes the number of inversions decreases with increasing duration, almost half the episodes lasting for only one observation. Short durations like this are probably largely accounted for by frontal inversions, which, even if they can be identified for a day or two, rapidly change elevation and seldom persist except in the case of almost stationary fronts. Single observation inversions occur in each layer with the following frequencies : (0.25-0.5 km) 51 per cent, (0.5-1 km) 27 per cent, (1-2 km) 37 per cent, (2-3 km) 61 per cent, and (3-4 km) 85 per cent. This suggests that inversion persistence decreases above and below the layer 500-2,000 metres. In particular the level between 500 and 1,000 metres shows a pronounced tendency for persistent inversions ; 13 per cent of those lasting more than two days lasted a week.

A breakdown of Table 12.3 into its seasonal components can be seen in Table 12.4. In terms of the number of inversions there is no significant difference between the seasons with roughly the same number occurring at all times of the year. This is in sharp contrast to the

Table 12.3 Inversion Occurrences at Long Kesh 1971-77

Duration (Hours)	Altitude (km.)				
	0.25-0.5	0.5-1.0	1.0-2.0	2.0-3.0	3.0-4.0
Less than 12	51	41	175	164	91
12-24	23	32	96	58	9
24-48	20	26	86	25	3
48-72	7	21	52	7	
72-96		12	24	3	
96-120		6	17	1	
120-168		7	20	1	
168-216		5	3		
216-		2	1		

Table 12.4 Seasonal Occurrences of Inversions at Long Kesh 1971-77

Duration (hours)	Altitude (km.) 0.25-0.5				0.5-1.0				1.0-2.0				2.0-3.0				3.0-4.0			
	Sp.	S	A	W	Sp.	S	A	W	Sp.	S	A	W	Sp.	S	A	W	Sp.	S	A	W
Less than 12	16	10	13	12	14	7	13	7	52	40	45	38	55	43	32	34	22	13	33	23
12-24	4	6	8	5	5	7	7	13	21	22	27	26	15	13	17	13	1	1	4	3
24-48	8	6	4	2	8	10	4	4	20	22	22	22	7	5	8	5			2	1
48-72	4		2	1	6	3	7	5	12	15	12	13	4	3						
72-96					1	4	2	5	7	8	3	6		2	1					
96-120					2		2	2	3	4	6	4		1						
120-168					1	2	3	1	7	8	2	3								
168-216					1	1	2	2		2	1									
216-							1													
Total	32	22	27	20	38	34	41	39	122	121	118	112	81	67	58	52	23	14	39	27
Mean Duration (hrs.)	21.8	17.5	18.0	14.7	38.4	44.8	53.9	48.3	33.2	41.1	30.9	32.5	13.5	16.8	15.0	11.9	6.5	6.9	8.8	8.4

Sp. Spring S. Summer A. Autumn W. Winter findings of Voloshin (1973) and is certainly a reflection of the maritime location of Long Kesh. In addition to the effect of the sea other influences can also be identified.

Inversion persistency does however show seasonality. If inversions persisting over two days are considered then summer stands out from the other three seasons as having up to 25 per cent more in this category. On closer examination these fall mainly in the 1,000-2,000 metres range. Good summers in the British Isles are charactertised by high pressure systems which either extend or break off from the summer Azores' anticyclone (Manley, 1952). This would produce the fairly persistent inversion described.

For each height category a spread of inversion durations ranging from less than twelve hours to over nine days is obtained. From this the mean duration of episodes whose mean inversion height lay at that altitude can be calculated. These values can be seen at the foot of Table 12.4. They are, however, more informative if plotted adjacent to each other and this has been done in Fig. 12.1 in order to illustrate seasonal variation. The increased persistency in summer at higher altitudes again stands out. Apart from this the only obvious seasonal differences relate to spring and autumn persistencies from 500-1,000 metres. During the spring the sea around Ireland is at its warmest in relation to the land. This introduces elements of instability into the lower atmosphere, causing an increased incidence of unsettled weather, hindering the development of long inversion periods. By contrast, in autumn, the sea temperature is close to air temperature, no marked instability exists, and blocking anticyclones are common in the stable conditions which characterise the season. Kelly and Wright (1978) noted seasonal variations in the preferred location of surface blocking anticyclones which suggest an increased incidence of such occurrences in northwestern Europe in late October. This would explain the contrast

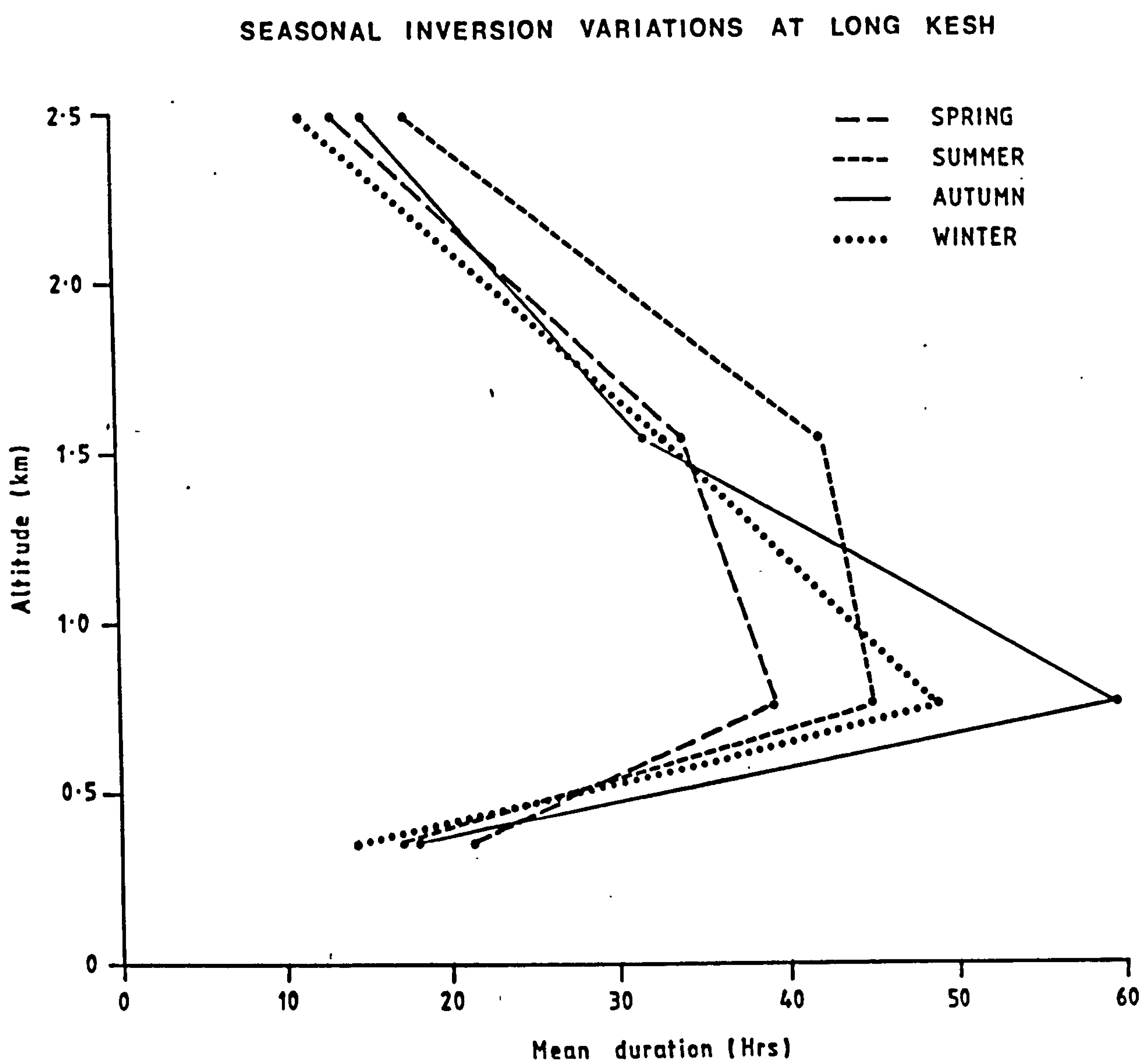


Fig. 12.1 Seasonal Inversion Variations at Long Kesh

between spring and autumn durations which is observed.

Where an inversion lasts three or more days it is almost certainly in association with subsidence from a slow moving anticyclone. This can quickly be confirmed by a glance at the plot of surface pressure corresponding to these periods. The behaviour of the inversion during these times closely mirrors the movement of the high pressure system, falling to a minimum height as subsidence reaches its peak, then rising as the anticyclone moves away. A sample study revealed that the height difference between the start of the period and the achievement of mean minimum level to be of the order of 1,400 metres. The lowest level reached, on average about 1,000 metres, occurred between two and three days after entry. The rate of descent which this corresponds to thus agrees well with that found by Holzworth (1972) for the principal subsidence inversion during the Thanksgiving Week Air Pollution Episode in New York, between 0.6 and 0.8 centimetres per second.

Persistent inversions whose mean levels are below about 700 metres might represent cases where, for at least part of the time, the inversion fell close to ground level. This is significant from a pollution viewpoint since it greatly restricts the mixing layer over a wide area. For one four day occurrence in April 1974, when the Long Kesh subsidence inversion fell close to ground level, sulphur dioxide concentrations at Linwood were 315, 225, 222 and 228 $\mu g/m^3$. This compares to the long term average of 53 $\mu g/m^3$. Fig. 12.2 shows the mean behaviour of such features based on a year's sample from Long Kesh. On the basis of Table 12.3 about one in four persistent inversions of this kind might be expected to fall to near ground level.

The trapping of pollutants below this falling inversion lid can be visualised. Reference has already been made to the effect of such features acting in conjunction with intermittent surface inversions. As these latter are dissipated each morning successive periods of fumigation occur as more polluted air is brought to the surface. This

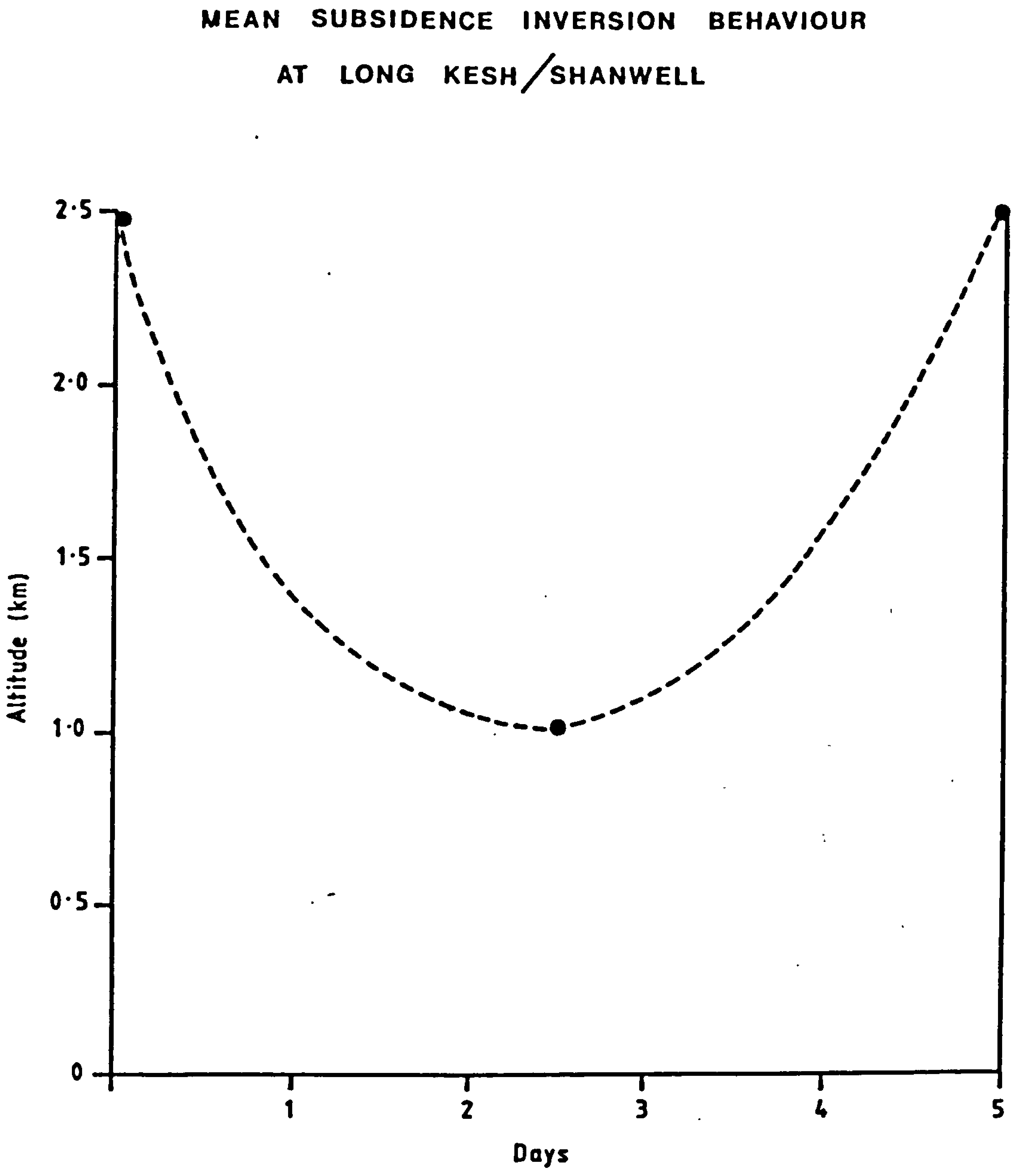


Fig. 12.2 Mean Subsidence Inversion Behaviour at Long Kesh/Shanwell

was pointed out by Halstead (1976) and is clearly visible in Holzworth's data for the Thanksgiving Week Episode. Similar conditions have been observed, in West Central Scotland on several occasions in the six year study period. Frequently, however, such occurrences are exacerbated by the effect of cold air katabatic flows from the surrounding moorland plateaux.

Voloshin (1973) suggested that the frequency of prolonged inversion periods could be represented by a Poisson distribution. If this is so, the probability of such periods occurring during a month or season could be predicted, quantities which could prove useful in calculations of worst case concentrations from particular sources. Before applying the distribution to the Long Kesh data, however, several prerequisites must be satisfied.

Firstly, the qualities of the Poisson distribution may only be derived from a flow of events which are independent of each other. Neither can two or more such events occur at the same time. These requirements are satisfied automatically in the criteria used for selecting inversion episodes. The Poisson distribution also requires that events are distributed with equal mean density. Following the precedent set by Voloshin this demand was satisfied by reducing the time interval during which the episodes were analysed to one month. For each month therefore episodes persisting over three days were considered. The beginning of such a period was taken as unit case regardless of how long the observation continued thereafter. This eliminated after effects. For each of the 72 months, the number of beginnings of extended inversion periods was counted (Table 12.5). The distribution of these values were then compared with the values which the Poisson distribution would have predicted. This quantity was calculated from the Poisson probability formula

$$P = \frac{a^k}{k!} . e^{-a}$$

where a = average value for the set of data, k is the number of sections involved, and e = 2.7183.

Table 12.5 No. of Extended Inversion Periods ($>$ 72 hrs.) at Long Kesh 1971-77

	1971	1972	1973	1974	1975	1976	1977	Total
Jan.		1	3	1	2	0	0	7
Feb.		1	2	0	2	2	0	7
March		1	3	1	2	2	1	10
April		3	1	1	0	2	1	8
May		0	0	1	4	0	0	5
June	2	1	4	3	0	2		12
July	1	0	2	2	2	3		10
August	3	2	1	1	0	2		9
Sept.	4	2	1	1	1	1		10
Oct.	1	1	1	1	1	0		5
Nov.	2	1	1	0	2	1		7
Dec.	2	1	4	1	1	1		10

Mean Monthly Occurence = 1.39

Table 12.6 shows the observed and Poisson predicted distributions for inversion periods over three days at Long Kesh. Agreement between the two sets of values appears good. The discrepancies apparent might have been even smaller had a data run of more than six years been possible. To establish whether or not the sample used approximates sufficiently close to the Poisson distribution to enable the calculation of probabilities a further statistical test was applied. The Kolmogorov-Smirnov test is a test of significant difference between two sets of ordinal data. If this difference is shown to be not significant at a particular critical value then it can be assumed that the Poisson distribution law is satisfied.

The actual and observed probabilities can again be seen in Table 12.7. Both sets of cumulative values have also been calculated. It is with the largest difference (0.053) between these two values that the Kolomogorov-Smirnov test is concerned. Reference to the appropriate table of significant values (Gregory, 1963) shows that for the given sample size this difference is not significant at the 0.1% level, implying acceptance of the null hypothesis. Thus it would appear that extended inversion occurrences at Long Kesh obey the Poisson distribution law. Thus the probabilities of given inversion durations in a month can be calculated and are those seen in Table 12.6. Further work could establish seasonal and altitudinal variations in these values.

In summary therefore it has been seen that problems of classification make for difficult comparisons between areas in terms of their inversion characteristics. It would nevertheless appear safe to conclude that Long Kesh is fairly representative of much of the north western quadrant of the British Isles. Temperature inversions occur here about three days out of five, mostly between one and two kilometres in height but occur with the greatest persistencies at lower heights i.e. between five hundred and one thousand metres high. Variations in seasonal frequency are slight and may relate to fluctuations in the importance of thermal and dynamical factors both in the

Table 12.6 Observed and Poisson Probabilities - Inversion Periods over 3 days at Long Kesh 1971-77

No. of Occurrences	No. of Months	Actual Probability	Poisson Probability
0	14	0.194	0.247
1	30	0.417	0.343
2	18	0.250	0.238
3	6	0.083	0.110
4	4	0.056	0.038

Table 12.7 Kolmogorov - Smirnov Test - Extended Inversions at Long Kesh

Probabilities Observed	Probabilities Poisson	Cumulative Probabilities Observed	Cumulative Probabilities Poisson	Mod. Difference
0.194	0.247	0.194	0.247	0.053
0.417	0.343	0.611	0.590	0.021
0.250	0.238	0.861	0.828	0.033
0.083	0.110	0.944	0.938	0.006
0.056	0.038	1.000	0.976	0.024

air and adjacent sea, though this requires further study. Certainly an investigation of anticyclonic occurrences would help towards understanding this and also the behaviour of inversions during such episodes. The importance of the latter has been demonstrated by Halstead (1973) for managing sulphur dioxide concentrations in the Glasgow Basin. But in general, greater knowledge will facilitate a better use of the dispersive capabilities of the atmosphere, something increasingly important in the future.

CHAPTER 13

PERIODS OF ENHANCED CONCENTRATIONS : CAUSES AND CASE STUDIES

13.1 Air Pollution as an Environmental Hazard

Despite the achievements made by man since the industrial revolution in harnessing and utilising the forces of nature his susceptibility to natural hazards remains. Vulnerability is most marked among the developing countries of Asia, Africa and Latin America where annual deaths from natural disasters continue to rise (Burton et al, 1978). Comparative death rates in the industrialized countries are lower, though material losses increase annually at a dramatic rate (Dworkin, 1974). Such trends are, however, almost inevitable in a world whose population has grown by 2.25 thousand million in the present century, particularly since this has led to a spatial distribution of people and their property which has greatly increased the susceptibility of both to natural hazards. Occupation of marginal areas, whether in response to population or economic pressures ultimately involves a trade-off between the short term social and economic benefits accruing and the potential for disaster looming in the long term.

Such decisions are made on an individual basis which implies some kind of appraisal of possible future events. This subjective estimation has been investigated by many workers (e.g. Saarinen, 1966, Ardsol et al, 1964, Bryson, 1974, Simon, 1956) who concluded that the degree of awareness of hazard potential is related to the extent to which the resource is needed and the gravity of other social and economic problems. This is a very significant conclusion in the field of air pollution with implications for the development of control policies not just in the United Kingdom but throughout the world.

Although in a global perspective anthropogenically derived air pollution is dwarfed by natural emissions, in a local perspective severe air pollution episodes are akin to natural disasters. Instead of population pressure forcing the over exploitation of a resource, it is the social, economic and political forces which demand an improved material standard of living and hence maximum exploitation of the dispersive capability of the atmosphere. The social and economic benefits of a new oil-fired power station are easily stressed. To balance, or attempt to balance these benefits against adverse effects occurring only very occasionally is frequently unpopular, often described as scaremongering, or even downright unpatriotic. This can be illustrated by the change in public attitudes towards air pollution episodes following the killing London smog of 1952. Prior to this, air pollution was regarded as a localised problem, a price not too high to pay for enjoying a relatively high standard of living. This consensus of opinion changed dramatically following the 1952 episode which could be described as a catalyst in transforming public attitudes towards air pollution. This shift in opinion led to the Beaver Report and subsequently to the Clean Air Acts. Increasing awareness of air pollution as an environmental hazard has accompanied every increasing estimates of its annual cost, now running in the region of £1,000 M p.a. (Burton et al, 1978).

Damage to plants resulting in excessive leaf drop occurs when SO_2 concentrations exceed 85 $\mu g/m^3$ (U.S.D.H.E.W., 1969, 1970, 1971). Accelerated deterioration of building materials may also be expected when mean concentrations exceed this level. Examination of the frequency distribution of sulphur dioxide concentrations at Linwood over the years 1971-1979 showed that levels in excess of this were experienced for 16% of the time. At the higher level of 120 $\mu g/m^3$, with comparable smoke concentrations, the frequency and severity of respiratory disorders in children increases, as does mortality among the elderly with similar disorders (see Chapter 2). Sulphur dioxide levels exceeded 120 $\mu g/m^3$ at Linwood for about 6.5% of the eight year period. Fortunately a similar level for smoke was only half as frequent, and the two did not always occur simultaneously, alleviating somewhat the adverse effects described above.

It is, however, with concentrations in excess of these values that this section of the study is concerned. O'Hare (1974) has noted that with a 24 hour mean value between 300 and 500 $\mu g/m^3$ there is a noticeable increase in the hospital admission rate among elderly bronchitics. While only five such occasions were recorded at Linwood during the eight year period, they were much more frequent nearer the city centre, where values in excess of 500 $\mu g/m^3$ occurred about twice yearly in the most polluted areas. Almost all of these higher values and the thirty or so occasions when SO_2 was between 200 and 300 $\mu g/m^3$ at Linwood represent extended periods of enhanced pollution during winter fogs. The importance of these features is thus evident, meriting further investigation of their nature, formation, dissipation and their role in restricting the dispersal of smoke and sulphur dioxide emissions.

13.2 Fog

The Glasgow Basin has a reputation for bad fogs, one of which in November 1909 is frequently cited in works on air pollution. In recent years the general improvement in air quality has resulted in a considerably reduced frequency of occurrence of dense fogs, already mentioned in Chapter 3 (see Fig. 3.6). Due to the physical configuration of the Basin, however, elimination of all fogs by an improvement in air quality is not feasible and occasional episodes remain inevitable. Saturation of the air close to the ground is encouraged on 'radiation' nights by the shelter of the surrounding hills, and their role as sources of cold air which drains into the lower valley, creating a shallow surface based nocturnal inversion. The basin may thus be considered an enormous frost hollow.

Analysis of the thermohygrograph traces, especially the three humidity traces, and personal observations made on the Gleniffer Braes tends to suggest that dense fogs in the basin frequently have well defined tops, in the general altitude range 150-200 metres O.D. Such fog tops need not coincide with an inversion, but can often do so, and in these circumstances a fairly effective trapping situation occurs in which all but the most buoyant of emissions from within the Clyde Valley are trapped at low levels, building up to the high concentrations observed.

Fog forms when air close to the surface is cooled, resulting in some of its water vapour being shed, condensing round some suspended nuclei such as ammonium sulphate. This is a similar mechanism to that which results in dew deposition, implying that the conditions favouring outgoing radiation, and surface inversion formation, also favour fog formation. The control determining whether dew or fog results is provided by the all important element of turbulence. This was noticed as long ago as 1917 by Taylor (1917) when he said, "......if the dryness caused by the deposition of dew on the ground diffuses upwards at a greater rate than the coldness is conducted upwards, fog is less likely to form than if the reverse conditions hold." Monteith (1957) noted that the rate of dew deposition decreased dramatically when the wind speed at 2 metres fell below 0.5 m/s, while Roach et al (1976) observed maximum fog development during lulls when the wind fell below this value. It would thus appear that radiative cooling tends to favour fog formation at the expense of dew deposition when turbulence is minimal, and vice versa when turbulence effects are more marked. Such conclusions however refer only to radiation fog, an important distinction which must be remembered before Roach's models, based on observations at Cardington, Bedfordshire, are applied to the Clyde Basin situation.

In such circumstances when turbulent diffusion is slight the air near the surface will undergo nearly the same degree of cooling as the surface itself. Once this layer cools sufficiently for condensation to occur the resulting shallow fog effectively traps long wave radiation from the ground, restricting further cooling and preventing any rapid upward progression of the fog layer. Slow cooling then occurs principally from radiation from the fog top, now the effective surface. In contrast to such a slow formation process, however, dissipation of a radiation fog can be very rapid, in one or both of two ways. Firstly, mechanical dispersal in association with an increased wind speed can occur as the synoptic situation changes. Perhaps the fog was associated with an anticyclone, which, moving off, permits more vigorous winds ahead of a depression to move in. Secondly, however, the radiation regime can be disrupted by the advection of cloud cover into the area. For one of the episodes under examination the almost spectacular effect of cloud cover on fog dissipation was demonstrated. Saunders (1960) found that the lower the cloud base was the faster the fog dispersed. The ability of cloud cover to clear fogs is of course primarily a function of its role in restricting outgoing radiation from both the ground and the fog top. This was confirmed by Brown and Roach (1976) in a numerical modelling study of radiation fogs which showed a marked reduction in surface net radiation and in radiative cooling near the fog top consequent on the advection of cloud cover. Saunders (1960) had in an earlier study found much the same thing in a different fashion, having paid particular attention to the soil-air temperature gradient. Where this was large, clearance was particularly rapid.

Examination of the fog characteristics associated with some of the high pollution episodes mentioned earlier quickly revealed that the theoretical chain of events following initial fog formation, as described above were most unhelpful when it came to comparing the situation in West Central Scotland with that of Cardington where much of the above research was centred. In particular, two characteristics of most, if not all, of the fogs observed in the Glasgow basin were at variance with the theories outlined above.

Firstly, Roach's model describes the development of a shallow, ground based fog, perhaps only a few centimetres thick, and growing in depth only very slowly. In practice fogs in the Glasgow Basin thickened rapidly, often filling the valley to a depth of 100 metres or more. Secondly it was noted both from examination of the Abbotsinch cloud base recorder data, and from observation of fog development during the period of meteorological instrumentation maintenance on the hills to the west of the basin that Glasgow fogs often thickened from the top down, and not growing upwards from the surface as Roach described.

The answer to both of these irregularities lies in the neglect of turbulent diffusion parameters. Numerous authors have concluded that radiational cooling cannot by itself produce a deep fog, emphasising the role of turbulence (Rodhe, 1962). It could be argued that some degree of turbulence always exists and can never be ignored. Even in apparently flat locations like the Cardington site katabatic influences might be detected. Lawrence (1954) produced an anemogram for just this site clearly showing evidence of a south-south-easterly slope wind. The idea of there being such a katabatic component at Cardington is implicitly ignored by Roach.

In the Glasgow Basin it would appear that such a flow of cold air, perhaps only a few metres thick continually renews the air in contact with the ground ensuring continuing condensation and fog enhancement. This katabatic flow may on most occasions be too shallow to be noticeable on the thermohygrograph traces. On other occasions, however, it is detectable not as a continuous phenomenon but rather as a series of outbursts or pulses, one of which can be seen for example on the traces for Stanely and Gleniffer in Fig. 13.1. The development of the katabatic outburst draining off from the higher level can be clearly seen. Experimental evidence of this nature was hitherto unavailable for the Basin and the existence of such katabatic flows represents an added dimension which must be taken into consideration when explaining the rapid deepening of valley fogs in the Basin.

It would seem natural that these pulses would also coincide with lulls in the overall wind, however gentle the gradient. If this is so then Roach's observation that lulls in the wind coincided with periods of fog thickening may thus be explicable not as wind minima but as katabatic maxima. In fact the quasi periodic oscillations he detected (Roach, 1976) may in fact be almost entirely related to this phenomenon. Evidence in support of this can be found in work by Reiher (1936) who analysed katabatic flow on various magnitudes of slope. He found that a rhythmic pattern of katabatic outbursts with a period of about five minutes could be noticed on a very steep slope, while pulses with a period of up to twenty minutes on slopes as small as 1% were observed. The quasi periodic oscillations observed by Roach (1976) had a period of 10-15 minutes. It would appear that katabatic influences on fog formation should not be ignored, even on the most gentle of slopes.

The failure of the purely radiative considerations of Roach's model prompted a further search for work which might relate better to the observed situation in the Glasgow Basin. The most useful study was found to have been one conducted in upstate New York by Pilie et al (1975). This was based in a valley not too dissimilar from the Clyde

KATABATIC WINDS ON THE GLENIFFER BRAES

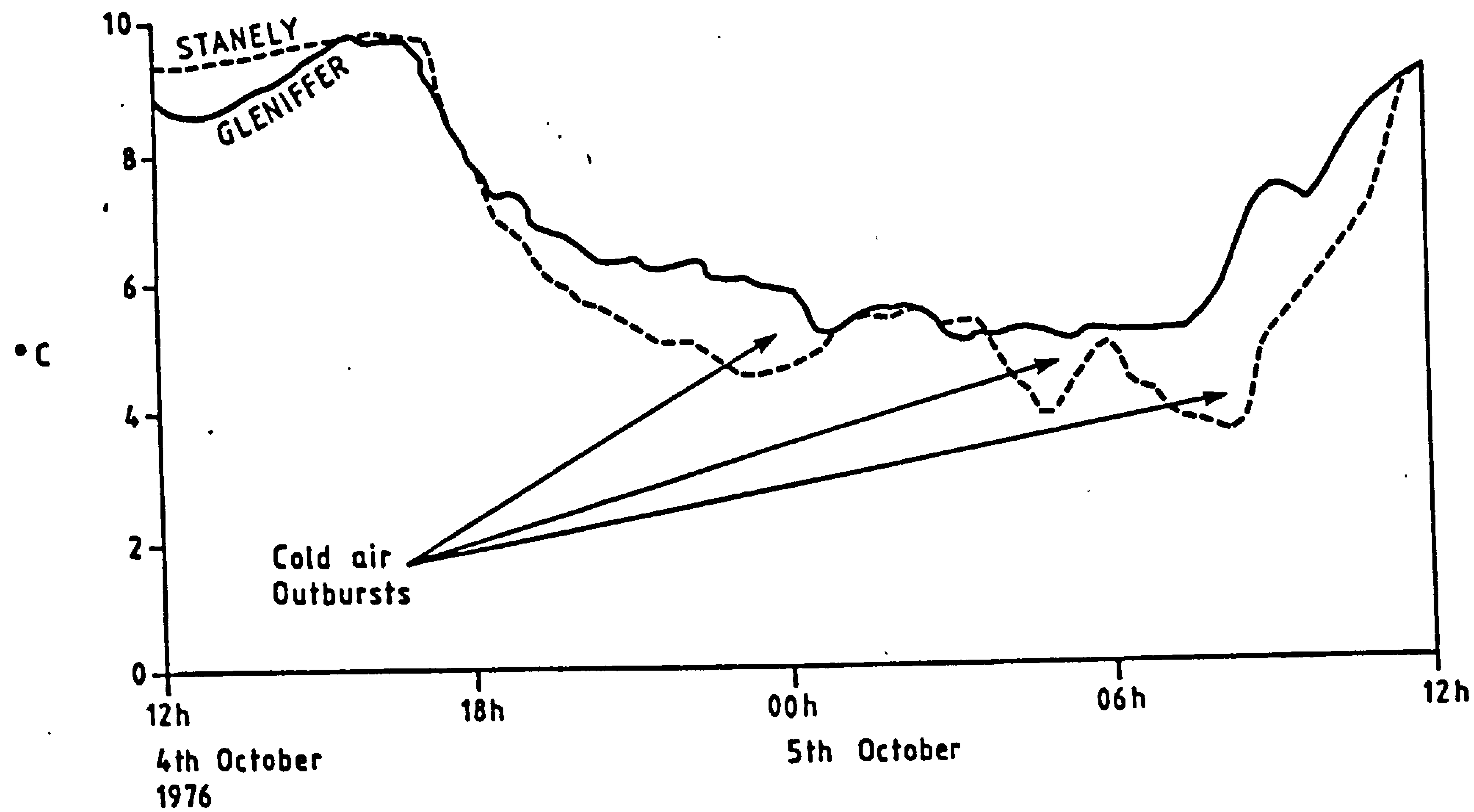


Fig. 13.1 Katabatic Winds on the Gleniffer Braes

valley, involving the extensive monitoring of eleven fogs and, as will be seen below, results agreed well with the Scottish experience.

Pilie argues that the temperature distribution leading to the formation of a valley fog is a result of nocturnal valley circulations of the type described by Defant (1951). This has several aspects leading initially to the production of fog aloft which is then propagated downwards. Initially radiative cooling of the valley slopes stimulates a katabatic downflow of cold air which contributes to the formation of a deep surface based inversion. Geiger (1965) has already suggested that this process begins within an hour of sunset and is accompanied by an upward return flow near the axis of the valley. Considerable dew depostion at the cold surface may be expected during this phase, and the upward motion at the valley centre consequently removes the cool, rather dry, air, causing a deepening dew point inversion. There comes a point, however, when the cold air pooled in the valley floor seeks an outlet, resulting in the establishment of a down valley mountain wind which inhibits any upward movement near the centre of the valley causing cooling in these low lying areas. The continuing downslope wind mixes with warmer air at mid levels in the valley and it is at this zone of contact that condensation occurs resulting in a layer of fog forming aloft.

Once the fog has formed it radiates, increasing the stability of the air at and immediately above the top. This contrasts with an unstable lapse persisting within and below the fog, resulting in the cold foggy air falling, to mix with the clear but almost saturated air below, which rapidly saturates producing a fog filled valley at least to middle levels. Pilie's model appears to explain better the behaviour of fog in its early formation stages in the Clyde Basin. However, both models are not in any sense mutually exclusive. Roach deals with radiation fog and therefore concentrates on the radiation regime to the virtual exclusion of turbulent diffusion considerations. Pilie is concerned with valley fog which is a product of air movement in areas restricted by relief. Thus airflow is the basis for his explanation which appears more in tune with the observed situation. With these views on fog formation and behaviour in mind it was decided to examine some of the periods of enhanced concentrations of smoke and SO_2 which occurred during fogs with a view to identifying the mechanisms behind the bad fogs for which the area is known.

13.3 Pollution Episodes Associated with Fog

(i) 16th-20th October 1975

Fog began to form late on the 16th during a period of change in the synoptic type over much of the country. Earlier in the day a shallow depression moving south westwards over the Irish Sea, had filled, producing a col over much of Britain on the 17th. A ridge of high pressure, extending from a Scandinavian centred anticyclone reached southwards over northern Scotland on the 18th and 19th, finally moving away eastwards as a strengthening southerly gradient approached from the west. Surface pressure at Abbotsinch rose from 1011 mb. at 16.00 hrs. on the 16th to 1025 mb. at 06.00 hrs. on the 19th. As with the majority of episodes analysed below, temperature data was collected from the three thermohygrographs, positioned in Stevenson screens about 1.25m above ground level. As was described in Chapter 4, to avoid the effects of the sun shining on the instruments the opening side faced north east. The instruments were calibrated with reference to standard thermometers, wet and dry, maximum and minimum, which were also housed in the screen. In general, exposure was adequate although the screen at Stanely was sheltered by a four foot wall on the uphill side. This was primarily for security reasons, important considerations in view of subsequent vandalism at the Gleniffer site which forced a premature end to the monitoring project at the three sites. The effect of such a wall was, however, visible in the results by way of a reduction in minor oscillations on the trace which were due to katabatic effects. This was not too much of a drawback, and in fact aided clearer interpretation of katabatic effects when compared with the other traces. Conditions of exposure in general conformed with recommendations made by the Meteorological Office (Air Ministry, 1950). As described in Chapter 4 the screens were located at various altitudes (2m, 100m, 250m O.D.) on the north facing slopes of the Gleniffer Braes to the south of the Glasgow Basin close to the Paisley area. Wind direction and speed and cloud base recorder data were obtained from Abbotsinch Airport.

From Fig. 13.2 it can be seen that fairly normal meteorological conditions for mid October prevailed in the two days preceeding the episode, with maximum temperatures at Abbotsinch between 10°C and 12°C and minima some 6°C lower. However, on the evening of the 16th the wind dropped below 2 knots. During the next three days it never exceeded 4 knots. With such light winds, and with a cloudless sky, thick fog rapidly developed by 22.00 hrs. By early on the 17th it can be seen that a temperature inversion of 5 centigrade degrees existed between the Abbotsinch trace and that of the top of the Gleniffer Braes at 250 metres O.D. Because of the failure of the intermediate thermohygrograph it is not clear whether this inversion was surface based throughout, or whether isothermal conditions within the fog gave way to an inversion immediately above the fog top. In any case, the fog top, as measured, on the cloud base recorder, varies in unison with the strength of the inversion between Abbotsinch and Gleniffer, the peak height of 200m corresponding to the time of maximum difference between the two stations. Since the fog top was always below the level of Gleniffer during this period it might be reasonable to suggest that it may have coincided with the inversion base during this time.

Fog is not normally expected to persist at this time of year. Apart from the fact that there is still considerable incident solar radiation the soil is often too warm at depth to permit the surface soil temperature to fall low enough to maintain a nocturnal air inversion in temperature throughout the day. Accordingly, a thinning of the fog around midday on the first day was forecast, correctly so, as can be seen on Fig. 13.2. Yet, even as early as 17.00 hrs. on the 17th, a mist began to develop which greatly thickened in the early hours of the 18th and persisted for over 24 hours. During this time the temperature at Abbotsinch was virtually constant, oscillating through less than 0.5°C in the 19 hours between 17.00 hrs. on the Friday evening and midday on the Saturday. During the same period the temperature on Gleniffer Brae fell from about 8°C to 2°C, coinciding with fog formation in the valley. On the cloud base recorder the top of the fog appears to be at about 160 metres suggesting that for much of the time Gleniffer may have

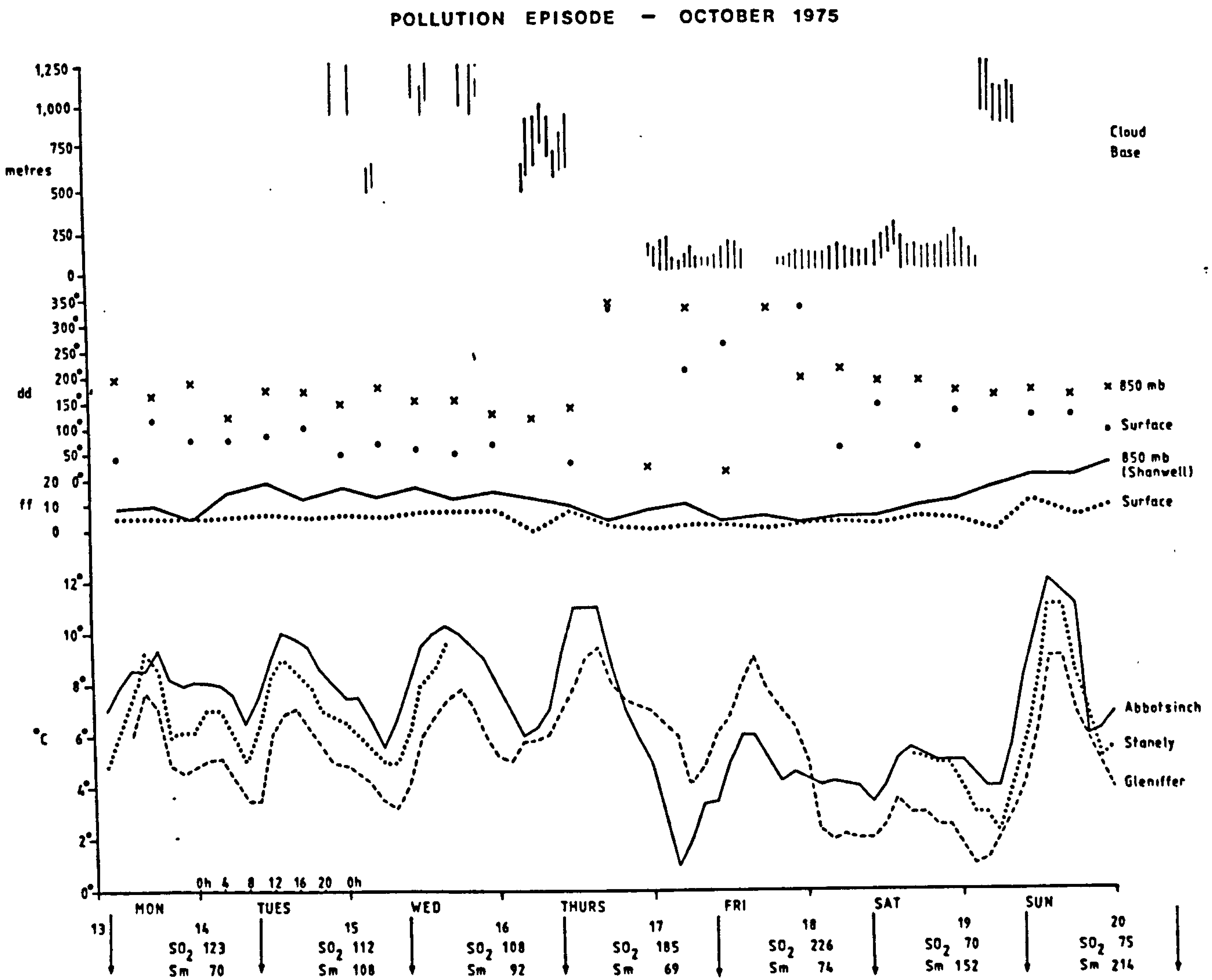


Fig. 13.2 Pollution Episode October 1975

been clear. This was not the case however at 13.00 hrs. on the Saturday when the Gleniffer site was shrouded in thick fog. It is clear from Fig. 13.2 that this was probably only a temporary occurrence representing a short period of raised fog for about four hours after midday.

The wind speed plot shows that both at Abbotsinch, and even at the 850 mb. level at Shanwell, extremely light winds prevailed. Such conditions would seem to favour the development of cold air drainage from the upland areas into the Basin. It must be remembered that as a result of the previous days' events a layer of cold air, close to its dew point lay in the Basin below about 150 metres. The 4°C level at Abbotsinch appears to represent the dew point of this layer. Once the cold air bursts began to encounter this moist layer even a small amount of cooling would produce saturation. This is what appears to have occurred. As Pilie suggested, the crossover point at which the inversion between upper and lower surfaces was destroyed was coincident with the fog formation. The moist air in the valley floor was thus chilled below its dew point by cold air katabatic flow down the valley side. Furthermore, the 2 knot wind varying in direction from 050°-150° observed at Abbotsinch during the period may represent Defant's mountain wind aligned along the axis of the valley, draining out the cold air pool produced from the katabatic inflow.

The fog persisted until early on the 19th. A strengthening southerly gradient was apparent by this time as a depression approached from the west. Accordingly the fog was expected to thin out to mist and low stratus. In part this occurred, although it was the arrival of stratocumulus over the area that resulted in a more rapid dispersal. Low cloud was first spotted in the Prestwick Airport cloud base recorder at 04.50 hrs. Less than 40 minutes later the fog at Abbotsinch cleared dramatically with the advection of this cloud deck. This can be clearly seen on the cloud base recorder data where the appearance of cloud at about 1,000 metres coincides with fog dispersal. The reasons for such a rapid dissipation have already been dealt with above.

Low temperatures were not a feature of this episode, frost at no time being observed. Partly because of this, emissions of smoke and SO_2 within the Basin might be expected to be considerably below their midwinter peak. This is perhaps why concentrations were relatively low, around 200 $\mu g/m^3$, particularly compared even with summer episodes (see Chapter 14). Nevertheless these values still represent a considerable enhancement of average values, illustrating how emissions are trapped below the inversion associated with such fogs and can accumulate with time to produce relatively high ground level concentrations.

(ii) 30th January -1st February 1977

Much higher concentrations, up to 433 $\mu g/m^3$ for SO_2, were observed during this midwinter episode when freezing fog filled the valley for a period of almost 36 hours. Anticyclonic conditions were again in evidence with surface pressure close to 1020 mb. and cloudless skies above the level of the fog throughout.

Temperatures at Abbotsinch first began to fall rapidly on the evening of the 30th, decreasing from $2^{o}C$ at 18.00 hrs. to $-5^{o}C$ at midnight. A slower fall was evident at Stanely, while temperature at Gleniffer changed only by less than $1^{o}C$ during the same period. Fog was observed to form in the early hours of the 31st, shortly after the establishment of inversion conditions between Gleniffer and Stanely. Considerable thickening, however, seems to have occurred a few hours later as the Abbotsinch temperature began to rise again, establishing a lapse between the valley floor and Gleniffer by 18.00 on the 31st. The continuing rise of all three temperatures throughout the early hours of the 1st, accompanied by an ever-strengthening wind led to thinning and dispersal around noon from the south (Fig. 13.3).

In many ways this episode was a typical, if more extreme, example of the mechanisms described in the first example. Maximum outgoing radiation initially led to the development of a shallow, moist surface layer of air which deepened due to inflow of cold air from the higher slopes,

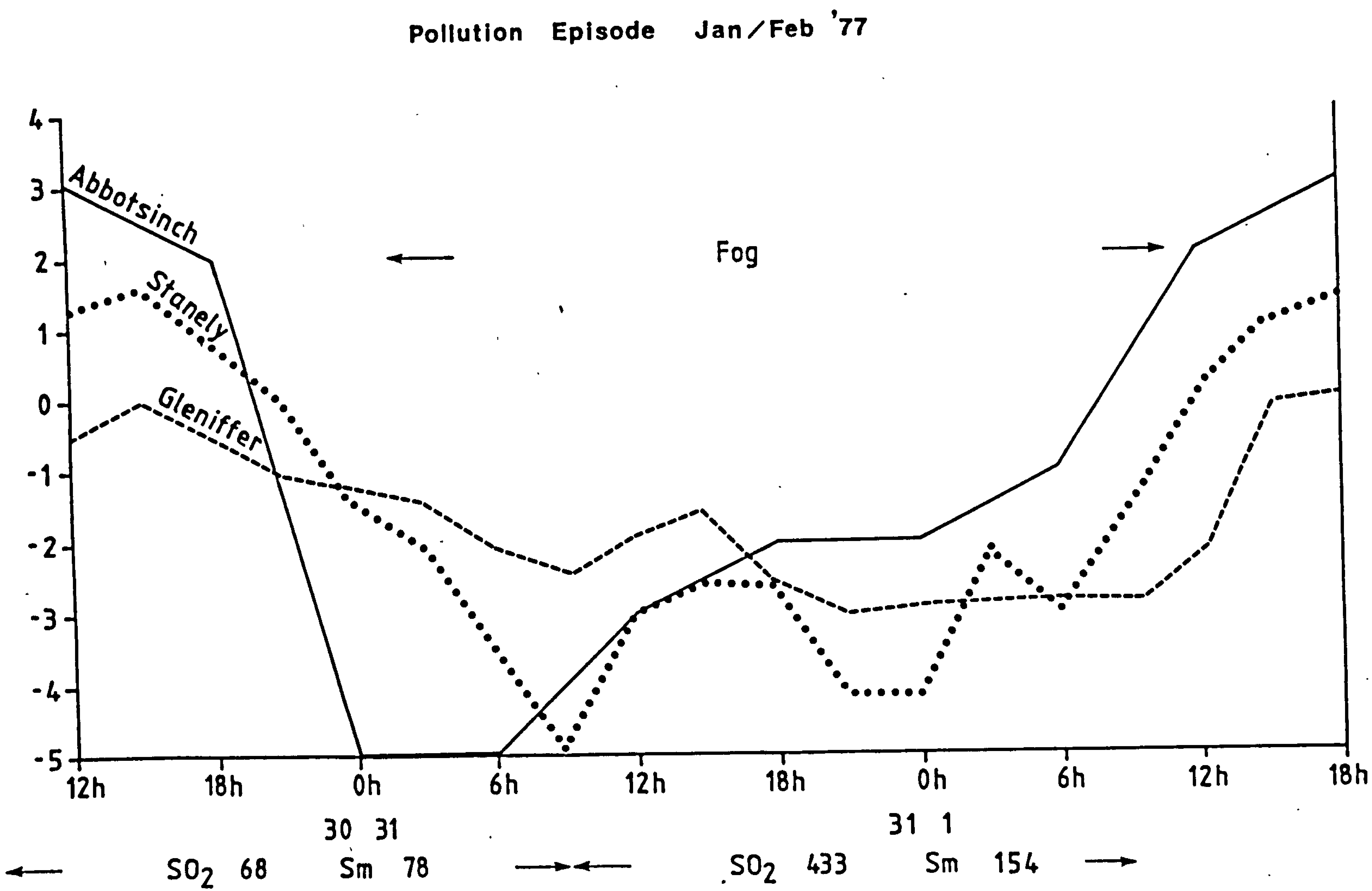


Fig. 13.3 Pollution Episode Jan./Feb. 1977

saturated, and fog formed. Because of the freezing nature of this fog the top was fairly clearly defined, lying at 170 metres at noon on the 31st. It is, however, worth noting that although no wind was recorded at Abbotsinch during the fog, there does appear to have been a westerly drift above the fog top. This is confirmed by reference to an anemograph from the top of the Centre One tax offices in East Kilbride. In contrast to the westerly drift apparent from the top of this twenty storey building, a similar instrument sited at a height of 10 metres above ground level on an adjoining building shows a greater tendency for southerly or even south easterly winds during the period. Evidence from Prestwick Airport on the night of the 31st/1st further confirms this, with hourly and ten minute mean wind values of 2-5 knots from south easterly directions. It would thus appear that some evidence for Defant's mountain wind appears to be present during this episode also, with a downvalley wind appearing to be in evidence, although the regional synoptic wind direction was west to east.

Further examination of the high level anemograph data shows that there appears to be periods of short duration, higher than average wind velocities during the latter half of the episode. During these pulses there is a tendency for the wind direction to swing round to the south or even slightly east of south, agreeing with the lower trace more closely. It could be suggested that such pulses represented bursts of downvalley winds, which are of sufficient depth to encompass the height of the building, thereby temporarily modifying the pre-existing wind field at this altitude. This would suggest that local valley winds of this type occur on a scale not fully appreciated hitherto and further suggest that at times the phenomenon is of sufficient magnitude to stir pollution down from fairly low level free air inversions. Tyson (1969) has documented a related occurrence of such a phenomenon at Pietermaritzburg in South Africa. The onset of the upvalley wind in the area is frequently associated with intense fumigation episodes as the low level wind reversal occurs. Perhaps a similar mechanism may explain the relatively high value of SO_2, 433 $\mu g/m^3$, observed at Linwood during this episode.

The importance of local relief in influencing local air circulation is thus evident, particularly in respect of downslope movement of cold air. Tyson (1968) has demonstrated the extent to which local relief can reverse and modify nocturnal airflows in the Drakensberg Mountains. It may well be that on a smaller scale similar effects, causing widespread fumigation of air pollutants, can now be confirmed for the Glasgow Basin.

(iii) 26th November-3rd December 1977

The most serious episode of enhanced pollution in the Basin occurred during the winter following the premature cessation of the temperature monitoring project. SO_2 levels at Linwood exceeded 580 $\mu g/m^3$. In the city centre peak levels of 980 $\mu g/m^3$ on a daily basis occurred at Glasgow 42. The episode therefore probably represents the worst occurrence since winter 1970-71, the winter before the Renfrew Air Pollution Project began.

As might be expected from such a case, no one set of factors was responsible. Instead a combination of unfavourable meteorological circumstances is apparent.

In the wake of a deep depression which crossed northern Scotland on the 23rd, an anticyclone moved south from Iceland to lie over Stornoway on the 25th. As pressure increased over the British Isles as a whole, the centre of this anticyclone moved south along the east coast of Scotland on the 27th and 28th, eventually being centred on the Irish Sea before crossing into Scotland again as it moved away into the North Sea on the 1st of December. Such a prolonged period close to the centre of the subsidence meant that most radiosonde stations in the northern half of Britain recorded an unbroken run of subsidence inversions on their daily ascents. This can be seen in Fig. 13.4 which shows the unbroken subsidence inversion at Stornoway, Shanwell and Aughton. The movement of the anticyclone in part explains the oscillation in the observed height of the inversion at the three stations. At Shanwell a notably persistent surface inversion is also apparent. In Such circumstances, it has already been noted, effluent

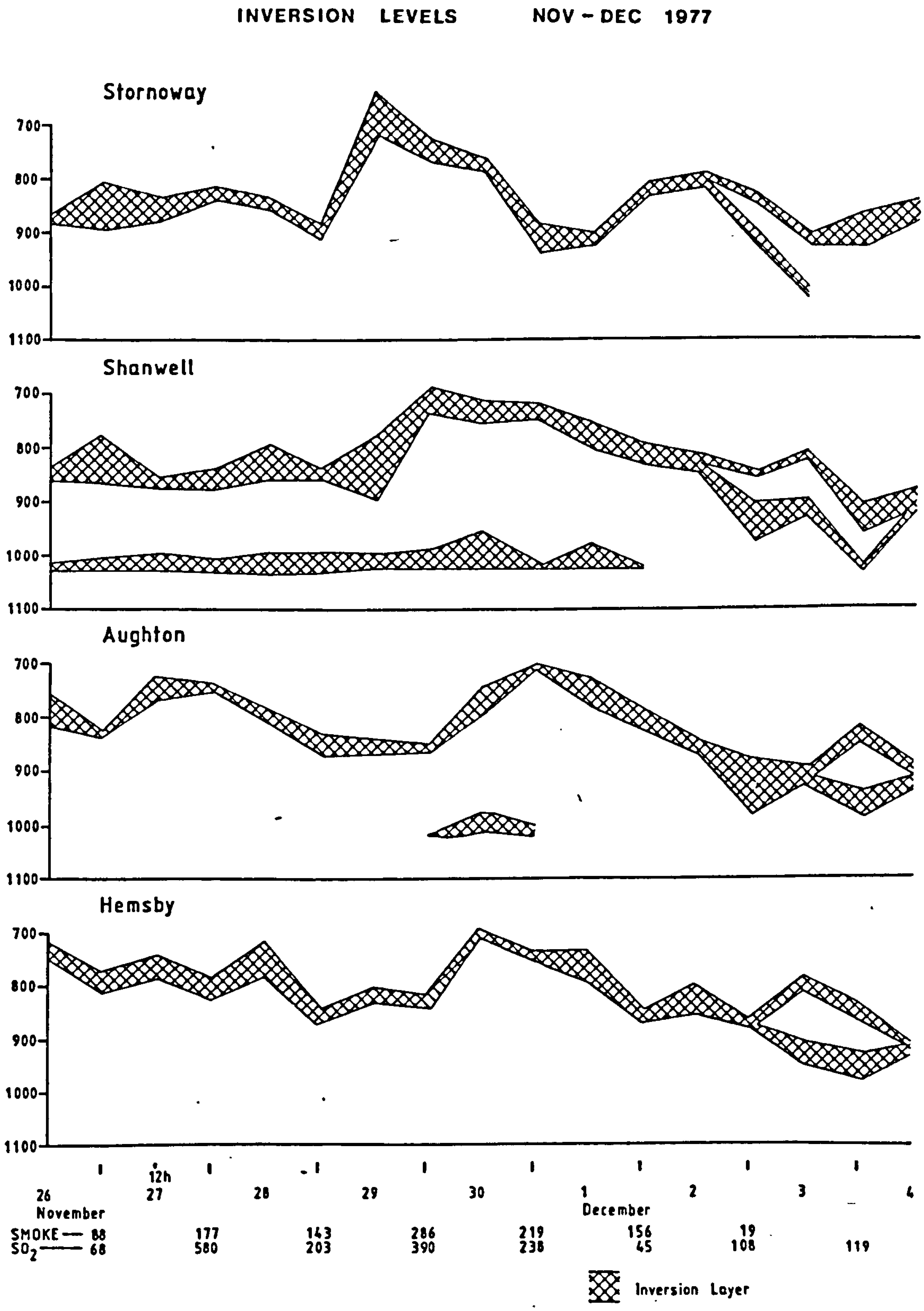


Fig. 13.4 Inversion Levels November/December 1977

plumes can be transported between these upper and lower inversion surfaces without marked dispersal. Evidence for this phenomenon can be seen in a photograph of the Longannet plume during the early part of the episode. Plate 2 shows the wind shear at about 250 metres which is affecting the Longannet plume in the early part of its rise. In the later part, near the point of maximum plume rise, the trapping effect of the higher subsidence inversion can be clearly seen. Stable conditions above and below have thus funnelled the plume into a rather narrow corridor of air along which the wind can transport it for a considerable distance without further dispersal. It is worth remarking that this day may well be recorded as the most polluted of the decade in the western half of the Basin. Furthermore, as was mentioned above, extremely high concentrations of SO_2 were recorded on the eastern margins of Glasgow, despite an easterly wind drift. Fumigation of the Longannet plume must thus have contributed considerably to overall pollution values in the Glasgow Basin as a whole.

A third major component in the episode was the existence of dense, freezing fog in the Glasgow Basin. In this respect circumstances must have been similar to those described above with katabatic flows exacerbating pollution levels. Temperatures of $-6^{o}C$ were recorded on both the 27th and 28th at Abbotsinch, and as low as $-10^{o}C$ at Crawfordjohn. Though wind directions were variable throughout the episode an easterly drift is apparent from anemograph data from Daldowie on the banks of the Clyde to the south east of Glasgow (Fig. 13.5). Even at this relatively exposed site, where wind speeds are on average 30% greater than that of Abbotsinch (Bower et al, 1979) almost a week elapsed in which wind speed failed to exceed 5 m/sec. During the period 28th-1st when wind speed was too light to move the anemometer cups, an easterly direction nevertheless registered. This may well be downvalley drainage of cold air as described above in (ii).

The episode came to an end late on the 1st when more vigorous easterlies gradually dispersed the fog. This was the first time for over four days that daily maximum temperatures at Abbotsinch exceeded $0^{o}C$, an indication of

Plate 2

The Longannet Plume 27th Nov. 1977

Plume buoyancy is enabling the effluent to penetrate a shallow surface inversion. Trapping, beneath a higher free air inversion, and subsequent funnelling in the direction of the Glasgow Basin are clearly apparent.

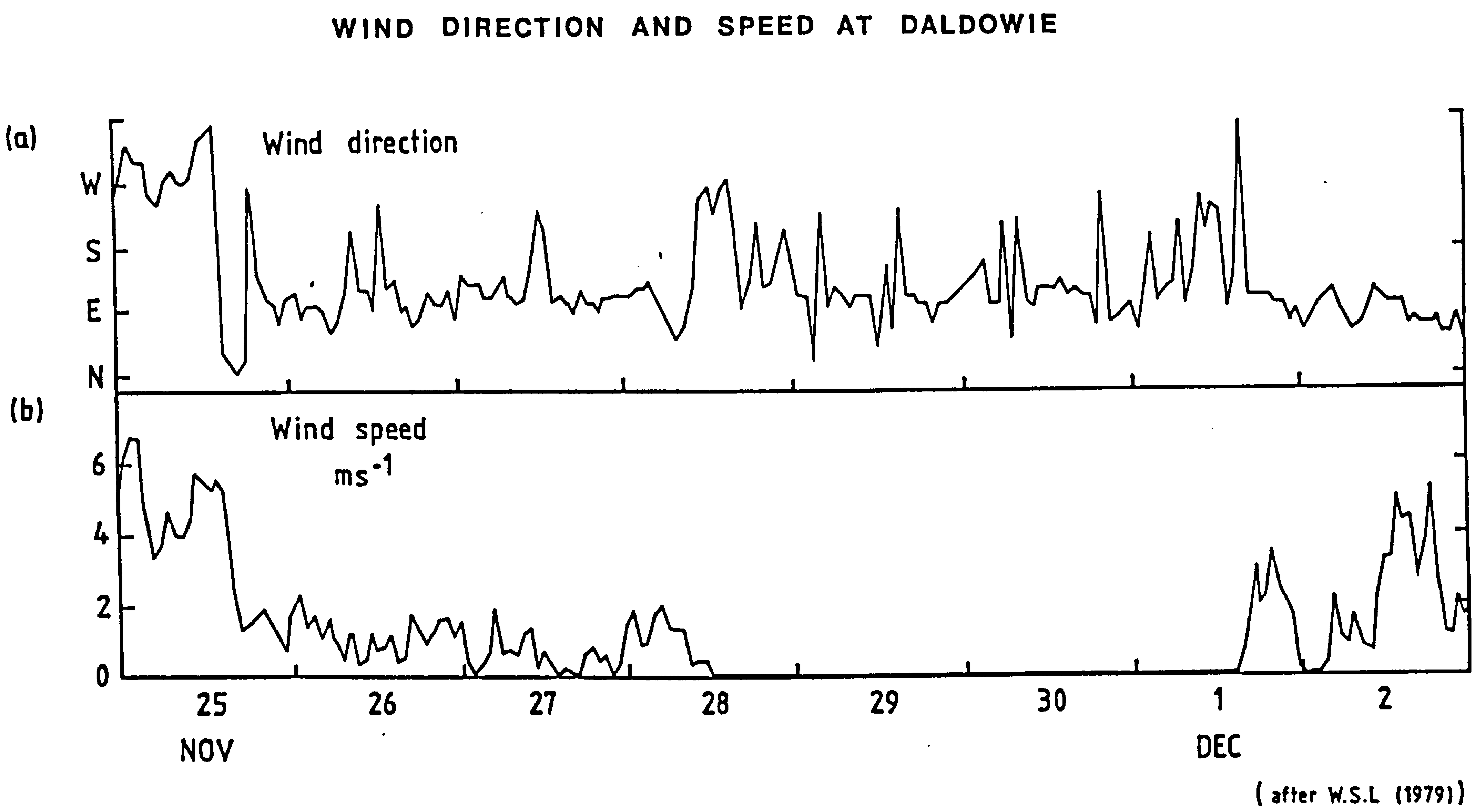


Fig. 13.5 Wind Conditions at Daldowie November/December 1977

the tendency for such fogs to persist once they become established.

Summary

It is clear from the above analysis that episodes of high pollution in winter are almost invariably associated with fog, despite the general reduction in fog frequency in recent years. Such occurrences remain significant principally because of their effect in sustaining a low level temperature inversion which traps most of the emissions made within the Glasgow Basin. Intense trapping appears to occur below the level of the surrounding hills, especially between 150-250 metres. During the most severe episode, described above, the incinerator plumes at Dawsholm and Linwood were the only plumes buoyant enough to penetrate the fog, an observation made from the Gleniffer Braes on the 27th November at the height of the episode. Pollution levels are further enhanced by downhill winds which drain into the basin on cloudless nights, bringing down from at least 300m the pollution that would normally remain at this level. The freezing fog which frequently occurs in winter under such circumstances often persists for several days, as occurred in the killing Glasgow Smog of November 1909. Additionally, however, pollution can also be imported into the basin when an easterly drift accompanies such conditions. This is itself most apparent when the existence of persistent subsidence and surface inversions outside the basin permits long distance transport of pollutants from the Forth Estuary. Such flows become entrained in the katabatic system on the edges of the basin and are drawn down into the valley floor further exacerbating pollution levels there.

There is, then, a 'mix' of atmospheric conditions which produce greatly increased levels of smoke and SO_2 in the basin. Some are fortunately rare and would be unlikely to occur in combination with any significant frequency. Other ingredients, however, commonly occur together and the severity of the ensuing pollution episode often depends on the degree to which the conditions possess these combinations in sufficient quantity to maintain persistence over a period of days.

CHAPTER 14

ENHANCED SULPHUR DIOXIDE CONCENTRATIONS IN SUMMER

14.1 Less Marked Meteorological Influences

During the process of data plotting it became clear that not all of the high pollution episodes were confined to the winter half of the year. Furthermore, peak levels were not exclusively coincident with periods of stagnant circulation during anticyclonic calms. High values of sulphur dioxide were observed on winds between 10 and 20 knots, seemingly at variance with the relationships established in Chapter 5, although it was noted that contributions from high level sources would be expected to be greater with such wind velocities. Garnett (1976) had previously noticed a similar phenomenon in her analysis of SO_2 trends in the Sheffield area. In general, however, it became apparent that relationships between SO_2 concentrations and meteorological parameters seemed to be less significant in summer than in winter. While the same meteorological controls are in evidence their effectiveness as agents influencing ground level concentration quantities appeared to be diminished during the summer months from April to the end of September.

To test the validity of this hypothesis it was decided to examine the relative importance of wind speed on SO_2 levels during the two seasons. For each day the average mean vector wind speed was matched to the corresponding SO_2 value at Linwood. Considering only winter data this gave a correlation coefficient of $r = -0.4236$, significant at 0.1%, between the two quantities. When summer data only were analysed this correlation fell to $r = -0.1538$, again significant at the 0.1% level. Thus it would appear that, at least as far as wind speed is concerned, concentrations of SO_2 are more sensitive to climatological parameters in winter than in summer.

Further verification of this conclusion can be found in the work of Leone et al (1966) who found that SO_2 concentrations behaved in a similar fashion in the New York area. It would also appear likely that had mixing height been chosen instead of wind speed a similar reduction in the correlation coefficient would have been observed. This would also have confirmed work by Markee (1961) who also observed the phenomenon using observations made from a television tower.

However, although the precise influence of meteorological parameters is more difficult to gauge in summer the effect on concentrations can be considerable on occasion. Table 5.1 shows the seasonal variation in SO_2 levels at Linwood from 1971-1979. It can be seen that summer 1976 was not only the most polluted season of that year, but was also the most polluted season between spring 1974 and winter 1978/79. Furthermore, the values of 60 $\mu g/m^3$ attained both in summer 1976 and 1977 are equal to the values which Keddie and Williams (1974) estimated as winter average equivalents exceeding the primary standards of the U.S. E.P.A. and the 'ill effects' level of the World Health Organisation, though only if accompanied by high smoke levels in the latter case.

During hot summer days solar heating of the ground contributes to intense turbulent exchanges of air between upper and lower levels. Pollution trapped aloft may be brought down to ground level by this overturning, at least partially explaining the pollution peaks frequently occurring in such heatwave conditions. Such a mechanism would, however, relate principally to high level emissions. Low level emissions appear to be restricted most under conditions which correspond more to cloudy summer weather. This was noted by Shevchuk (1966) in the U.S.S.R. and nearer home by Lawrence (1969) who showed that pollution values were highest in London whenever the sky was overcast by day and clear by night. The behaviour of the nocturnal surface inversion may well explain this. Such a situation might correspond to one where the surface inversion at night became uplifted during the day to a height at which effective trapping occurred, permitting the accumulation of pollution with the passage of time. Conditions approximating to these were noted in the Shanwell data for the first two weeks in July 1976. Concentrations at Linwood during this period averaged about 100 $\mu g/m^3$, more than double the mean summer SO_2 concentration value of 42 $\mu g/m^3$.

Sonkin and Khrapachenko (1973) emphasised the importance of persistence, which they described as 'meteorological inertia', during the summer months when pollution levels show a strong correlation with the previous day's values. A correlation coefficient of up to 0.81 was obtained which, while acceptable for a continental location like Chita in Eastern Siberia, would hardly seem applicable to the Scottish case. Summers in Western Scotland are rather more variable, as its inhabitants will testify, and accordingly, such a strong lag correlation was not to be expected. When the analysis was completed, using a recently developed facility in the S.P.S.S. programme package, a correlation co-efficient of $r = 0.7612$, significant at 0.1%, was obtained between SO_2 levels and those of the previous day, for summer. Such a value appears quite high in view of the contrasting locations of Chita and Linwood. In winter it falls to $r = 0.5733$ (significant at 0.1%) confirming the existence of the 'inertia' factor in summer. This is probably related to a greater frequency of slow moving synoptic features during this season.

It would appear, therefore, that summer enjoys distinctive differences in the manner in which meteorlogical influences disperse air pollution. Probably the best way of appreciating these influences at work is to examine periods when enhanced pollution was recorded. This is done below for two such periods, June/July 1975 and May 1976.

14.2 A Case Study in June/July 1975

The period was characterised by an anticyclone which remained slow moving to the south west of Scotland, before crossing the country and eventually moving away to the north east. In many ways the episode illustrates some of the points made earlier particularly in respect of the less marked influences which meteorological factors have on pollution dispersal in summer.

Wind directions varied considerably throughout the period without seeming drastically to affect concentrations. Likewise wind speeds of over 13 knots were recorded in conjunction with an SO_2 value of 216 $\mu g/m^3$. Mean levels of SO_2 were just below 200 $\mu g/m^3$ at Linwood for a period of 13 days, a prolonged period by any standard. Similar concentrations were also observed at the other two monitors at Erskine and Lochwinnoch.

Explanation of these high levels appears most convincing if based on the behaviour of temperature inversions below about 3,000 metres during the period (Fig. 14.1). Quite clearly the build up of pollution beneath a low level or falling inversion can be seen occurring from the 26th to the 29th. Peak values of 232 $\mu g/m^3$ occurred when this inversion reached its lowest level on the 29th. Thereafter, this already weak inversion seems to have dissipated, allowing pollution to mix with air up to the height of a higher inversion at about 1,700 metres. This increase in the volume of air available for mixing resulted in a fall in concentration to 168 $\mu g/m^3$. In the following three days however, this second inversion began to fall as renewed subsidence occurred, and by early on the 2nd its level was below 1,000 metres causing an increase in SO_2 concentrations to 225 $\mu g/m^3$.

There is no inversion on the Shanwell soundings on the 3rd or early on the 4th, with the exception of a high level weak feature which persisted at high altitudes throughout the episode. Despite this apparent absence of trapping, concentrations persisted at a high level, at least equalling the peak of

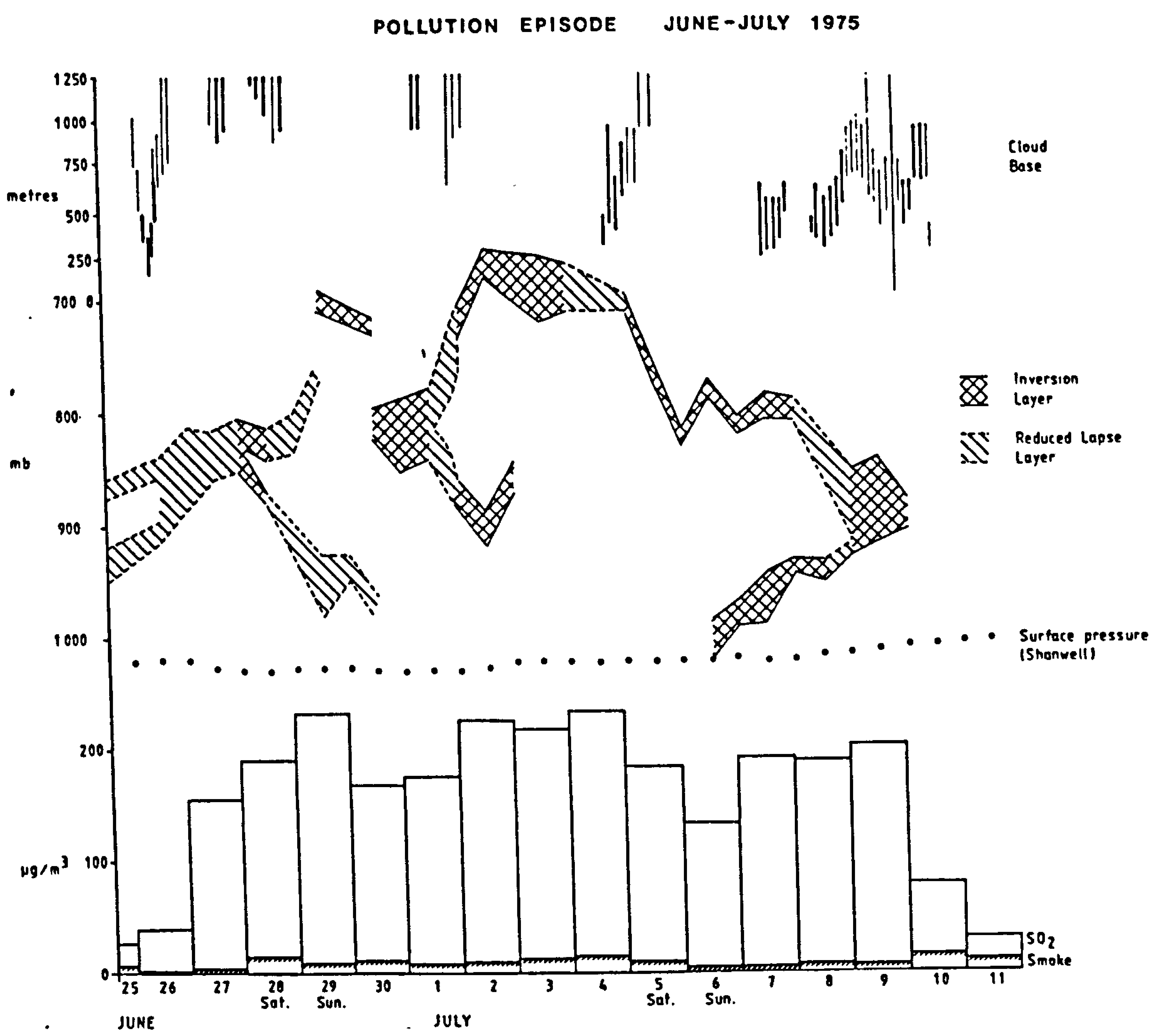


Fig. 14.1 Pollution Episode June/July 1975

232 $\mu g/m^3$ reached on the 28th/29th a week earlier. This seems explicable only in terms of a trapping inversion not recorded at Shanwell, but existing at Linwood. The existence of such features has already been suggested in Chapter 10. For this case, however, there does appear to be some vindication of the hypothesis due to the existence of cloud base recorder data from Abbotsinch. A rising cloud base at 300 metres can be clearly seen on the 4th, suggesting that an inversion existed at this altitude. Certainly the pollution values behave as might be expected with a lifting inversion, falling below 150 $\mu g/m^3$ for the first time during the episode. The lull proved only temporary, however, as a renewed burst of easterly winds from the 6th to the 9th provided further pollution. To some extent the build up was countered by a rising inversion level as pressure fell and the anticyclone moved away north east. By late on the 9th the inversion had disappeared and pollution values of 200 $\mu g/m^3$ on the 8th/9th fell to 77 $\mu g/m^3$ on the 9th/10th and 30 $\mu g/m^3$ on the 10th/11th as a westerly flow began to reassert itself.

It would seem that this episode would appear to exemplify many of the conclusions reached in this study regarding the effect and behaviour of subsidence inversions. Rising concentrations coinciding with falling inversion levels and vice versa, the persistency and variability of inversions, the less marked summer relationships, the inertia of concentrations over such a period, all are evident in this case study. Yet, paradoxically, this study could have utilised apparently more favourable meteorological conditions in almost any other summer, conditions which might have been expected to produce higher concentrations than those in question. In this respect the values obtained in this episode seemed anomalously high and the explanations offered above, while adequately explaining the relative variation in SO_2 concentrations do not explain their absolute values in terms of similar meteorological circumstances on other occasions.

Dissatisfaction with the extent to which the above explanation contributed to an understanding of such anomalously high levels led to a re-examination of the available data. It was noticed initially that the episode occurred during a typical summer heatwave with maximum temperatures at

Abbotsinch Airport reaching in excess of 26°C, and generally exceeding 20°C throughout the episode. Sunshine totals were similarly well above average, between 10 and 14 hours on most days and up to 15.6 hours on the 6th. Both parameters were plotted together with daily SO_2 levels and the results can be seen in Fig. 14.2.

Considering the plot of maximum temperature it can be seen that prior to the 27th, and following the 9th, the divergence between temperature and pollution values is large, and the two graphs appear to move in opposite directions. This is normally the case, especially in winter, when SO_2 values are more sensitive to changes in temperature. Domestic and industrial emissions (especially from power stations) are closely related to ambient temperature levels. The degree day index issued by British Gas as a means of predicting consumer demand has been shown to have a fairly strong inverse relationship with SO_2 levels (Elsom, 1976). From the 27th to the 9th, however, the two graphs appear to move much more in harmony with each other. This time period corresponds to the period of the episode. Though any relationship is not marked there is just a suggestion that SO_2 levels are directly proportional to maximum temperatures, particularly is a small time lag is allowed. While a tentative conclusion of this type is further reinforced when sunshine hours are also considered what is important to realise is that the previous relationship is no longer in evidence. Reversal of the inverse relationship between SO_2 and temperatures mentioned above has occurred during the period of the episode. This implies that a new component is operative, one not acting at lower temperatures. In such circumstances of high temperature and intense insolation a photochemical component was suspected.

The possible existence of significant pollution of photochemical origin has for long been ignored in the British Isles. Lacking the high temperatures, high sunshine levels, and high car ownership levels of California the British preoccupation with smoke and sulphur dioxide pollution has been understandable. More recent studies are however, changing these emphases slightly. Since the early seventies studies of secondary pollutants have grown in importance. In

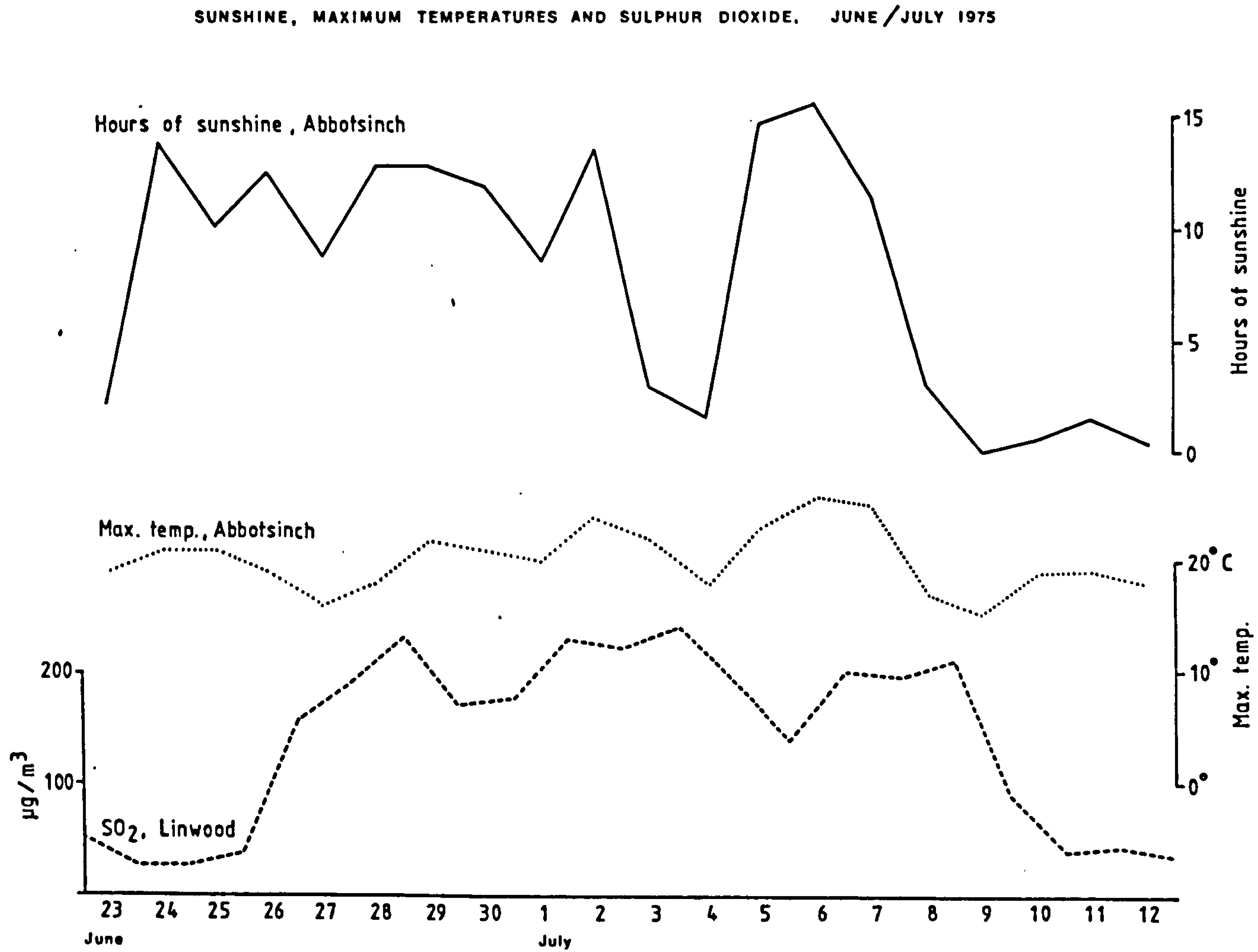


Fig. 14.2 Sunshine, Maximum Temperatures and Sulphur Dioxide June/July 1975

particular, elevated ozone levels measured at Adrigole on the West Coast of Ireland have lent support to the contention that ozone and its related secondary pollutants can be transported distances of up to 1,000 kms. (Cox et al, 1975). Warren Spring Laboratory has measured ozone, oxides of nitrogen and total hydrocarbons in Central London since July 1972. Correlation with meteorological variables has been achieved in which maximum daily temperature, relative humidity and daily insolation were found to be most significant, together yielding a multiple correlation co-efficient of 0.623 with ozone concentrations (Stewart et al, 1976). The relevance of these parameters to the episode in question seems obvious.

Of more significance to the episode under study, however, is recent work by Ball (1976) analysing ozone levels at three locations in Greater London. In addition to the three parameters found significant by Stewart et al (1976) Ball also stresses the 'key importance' of inversion conditions. Though unable to examine the role of inversion height he found that nocturnal inversions in particular enabled the build up of locally generated oxidant precursor pollutants such as oxides of nitrogen and various hydrocarbons. These chemicals subsequently became involved in photochemical reactions if conditions during daylight the following day were favourable, producing a maximum ozone concentration around noon. During one summer's observations Ball found that oxidant levels in excess of the Greater London Council's guidelines of 0.08 p.p.m. (on a one hour basis) occurred on about 15% of days. 0.08 p.p.m. corresponds to 160 $\mu g/m^3$ and is also the U.S. Environmental Protection Agency's primary standard. Adverse health effects are noted at 0.10 p.p.m. (Brodine, 1971). A recent study (Lynn, 1976) exposed a group of people to 0.5 p.p.m. ozone for three hours daily six days a week for 12 weeks, and another group to 0.2 p.p.m. for a similar period. These two levels approximated to a smoggy summer in Los Angeles and in other American cities respectively. No pulmonary effects were found for the latter group, but for the former there was a decrease in lung function as measured by forced expiratory volume. Exposure to levels less than 0.10 p.p.m. is also commonly known to cause eye irritation, throat irritation, and a greater frequency of headaches.

The highest hourly mean concentration observed by Ball (1976) in Central London was 0.15 p.p.m. A combination of the meteorological circumstances described above occurred at this time. The date on which this peak occurred was June 26th 1975, the day preceeding the onset of the pollution episode at Linwood ! Such a coincidence lends further support to the contention that some photochemical component was operative during this episode. The meteorological circumstances producing peak ozone pollution in London were not dissimilar to those experienced in Scotland over the following ten days and had ozone been monitored in the Glasgow Basin a marked increase would almost certainly have been noted.

Increased ozone levels explain the anomalously high 'SO_2' concentrations. In the presence of ozone, SO_2 in the atmosphere readily oxidises to sulphur trioxide and the solution of this highly soluble gas produces a sulphuric acid mist of low-concentration. Such a combination of sulphurous and sulphuric acid would require considerably more alkali in the titration process, thereby falsely indicating higher concentrations of sulphur dioxide than were actually occurring.

This represents the first measured evidence of photochemical pollution, however indirect, in Scotland, although the potential for such occurrences at such high latitudes has been appreciated for a few years (Mieber et al, 1976). This potential relates primarily, however, to internally generated pollutants, although for this particular case at least some of the ozone may well be of distant origin. In the south of England ozone of continental origin is a significant contribution to the relatively high levels mentioned. Nevertheless, the new dimension which this photochemical component introduces into future pollution studies involving summer data suggests that the monitoring of ozone levels within the Glasgow Basin might well yield significant results. The location of the Linwood monitor in this respect is a little disconcerting being close to the take-off path for Glasgow Airport. Hydrocarbon concentrations of various kinds may be anomalously high at this point.

14.3 Long Distance Transport of Sulphur Dioxide

The almost universal adoption of high stack dispersal policies implies a much greater interchange of pollution between adjacent areas than formerly existed in the era of multiple low level sources. An instance of this has already been shown for sources in Eastern Scotland which, by virtue of their buoyancy, are detected in the Glasgow Basin. In similar fashion, under the appropriate meteorological conditions, SO_2 from Inverkip will certainly appear in the Forth Valley monitors. The scale of the problem is however of a greater magnitude when long distance transport across international frontiers occurs, involving much more complex legal and political overtones. Nowhere is this better demonstrated than for the case of Scandinavia which claims considerable damage to forests and fish life from SO_2 imported from neighbouring industrial countries (Holt-Jensen, 1973). Nordoe (1974) provided quantitative estimates of the amounts of SO_2 involved while McMahon et al (1976) outlined the transportation model most applicable, one involving washout and dry deposition components. Industrial areas of Britain, the Low Countries, the Ruhr and Eastern Europe are often claimed to be the principal source areas for the SO_2 which causes the damage. More recent research, however, suggests that amounts transported across the North Sea are less than formerly thought and it would seem more reasonable to attribute environmental damage in Scandinavia to the combustion of fairly high sulphur content coal from East Germany and Poland (Barnes and Egleston, 1977).

More definite evidence of transport potential has come from American research. Breeding et al (1975) has monitored the urban plume from St. Louis for a distance beyond 120 kms. downwind, showing circumstances under which it remained a fairly discrete entity.

Such a potential for long distance effects has significant ecological implications apart from acid rain damage. Peakall (1976) outlined results showing abnormally high concentrations of D.D.T. in New York rainwater a few days after crop spraying with the chemical occurred in the Pacific northwest, over 3,500 kms. distant. This demonstrates not only the rate of air mass movement but also the consequent potential for environmental pollution to be experienced great distances from the original source. On a much smaller scale Barns (1975) has illustrated the transport of smoke and SO_2 into rural areas of England and Wales, producing a deterioration in air quality in previously unpolluted areas. This of course runs counter to the current E.E.C. guidelines (E.E.C. Commission, 1977) which are against control policies which export pollution in this way.

Pollution quantities attributable to distant sources outside Scotland are not readily detectable on the three monitors in Renfrewshire. Accordingly, only one case is documented below which is probably representative of meteorological conditions conducive to pollution of this type.

The scarcity of data of this type is largely a reflection of the rarity with which the requisite weather type occurs. Long distance transport obviously requires a laterally stable funnelling of pollutants beneath a temperature inversion. However, the relatively short duration of SO_2 in the atmosphere prior to its removal by the various scavenging processes necessitates also a fairly fresh wind to enable transport to take place prior to these processes occurring. The existence of such a wind velocity in association with inversion conditions is not common and explains why such instances are so scarce on the monitor records.

From the 21st to 26th May 1976 surface winds and those at about 850 mb. both had a south to south-easterly component and ranged in speed from 10-20 knots. An intermittent inversion appeared to exist slightly above this level on average at Shanwell, although at Aughton in Lancashire an almost unbroken inversion between 780 mb. and 900 mb. was apparent through this period. It is suggested that under such conditions emissions from industrial

Lancashire would be trapped at the base of this inversion and drift northwards on the fairly brisk southerly winds. Since wind velocities both at the surface and up to the base of the inversion differed relatively little, there being thus little wind shear in the vertical, stirring of this polluted air mass was unlikely to have occurred to any great extent, even passing over the Southern Uplands which would be still relatively cool at this time of year. On reaching the relatively warmer Central Lowlands of Scotland overturning of the lower levels of this polluted air mass could be postulated, resulting in fumigation. Such a mechanism could be advanced to explain the slightly elevated SO_2 levels (in excess of 90 $\mu g/m^3$) observed on southerly winds at Linwood during this period.

Such a mechanism would appear to suggest that a potential for long distance pollution transport exists within the British Isles. This has important implications for control policies based on high stack dispersal since it implies that such policies merely export pollution downwind. Long distance transport beneath an inversion coupled with fumigation has been observed by Garnett (1976) to result in very high concentrations in remote rural areas. Such mechanisms, taken in conjunction with the evidence of photochemical pollution presented above are further causes of instances of enhanced pollution in spring and summer and of a blurring of the winter/summer contrasts in pollution levels which formerly existed.

CHAPTER 15

INVERKIP POWER STATION : A CASE STUDY

The value of a study such as this must ultimately depend, at least in part, on its applicability to actual situations where air pollution considerations are involved. Not only do such circumstances enable a synthesis of the many and varied aspects of the problem which have been considered already, often by necessity under separate headings, but they also force the whole air pollution problem into a truer perspective amid an actual situation of competing and often conflicting priorities. For these reasons it was considered desirable to use the issues involved in planning and constructing Inverkip Power Station as a case study illustrating the practical utility of climatological research in minimising the harmful effects of air pollution. It was a fortunate coincidence that the development, the most significant source of sulphur dioxide planned in Scotland in recent years, took place both within the area of interest and within the time period encompassed by the present study.

15.1 The Background

The choice of Inverkip as a potential site for the South of Scotland Electricity Board's first (and so far only) completely new oil-fired power station was strongly influenced by two considerations. Firstly, since the generation of electricity is now exclusively a waterside industry in Scotland, such a coastal location offered access to the immense amounts of water needed for cooling purposes, thus obviating the need for unsightly cooling towers. Secondly, the location was close to the centre of demand in the Glasgow region thus minimising transmission costs.

The choice of oil as a fuel was made during the middle sixties at a time when supply exceeded demand throughout the world and oil prices were only a fraction of those pertaining today. A major component in this was the rapid exploitation of Libyan reserves. Allocation of prospecting blocks in Libya favoured the smaller independent oil companies at the expense of the major companies. This naturally led to a situation where new marketing outlets were sought by these companies. Western Europe, where refining capacity had doubled between 1960 and 1966, was regarded as a prime target for this attempt at market penetration. Britain offered such an opportunity, having a highly profitable and rapidly growing market for petroleum products of all kinds.

Such reasoning may have been behind the ultimately unsuccessful attempts by Murco and Socal to establish crude oil terminals and associated refineries at Wemyss Bay/ Longhaugh and Hunterston respectively. At that time neither company operated a refinery in the United Kingdom. This is still the case and both companies remain relatively unknown in Britain. Those major companies that are well established here had already invested heavily in places like Milford Haven and Fawley, and on the Humber, Thames and Tees estuaries. In this respect they are close to the main market concentrations in the English Midlands and the South East, and are most unlikely to be interested in expanding capacity on Clydeside for the foreseeable future.

The possibility of obtaining low cost fuel oil from the Murco development may have strengthened the S.S.E.B.'s preference for the Inverkip site. Of more importance, however, would seem to have been the advantage which the site had over alternatives at Longhaugh, Ardgowan, Irvine and Dundonald in terms of its access to cooling water. The engineering problems of Inverkip were relatively small. The deepwater channel lay close inshore and a brisk tidal current rapidly removed the hot water output while replenishing continually the cold water intake. Largely on these grounds the extra costs of locating at one or other of the alternative proposed sites were estimated at between £1M and £6M. Whether or not these amounts should have been considered significant in an initial projected cost of £92M which eventually escalated to £160M on completion remains questionable.

The second major influences in favour of a Clyde Estuary location was the need to match in a spatial context the supply and demand for power in Central Scotland. At that time Longannet and Cockenzie accounted for the bulk of the generating capacity of the Board and both lay in East Central Scotland. In contrast to this supply situation the region of principal demand lay to the west in the Glasgow region. The transmission of electricity between the two areas involved a power loss which would have increased if further generating capacity was located on the Forth rather than the Clyde Estuary. A power station on the Clyde Estuary, as close to the Glasgow conurbation as practicable would considerably alleviate the imbalance. Oil was the most favourable fuel for this station which was envisaged not as a baseload station but rather as one which catered for variations in demand. Coal and nuclear power stations are much more suited for baseload running due to their inflexibility and in the case of nuclear stations the difficulty of accurate regulation of the reaction. In any case Hunsteron B would meet the baseload requirements of much of the Western region while Longannet would do likewise for the Eastern areas. An oil-fired station offered the capability for rapid production during peak periods or even reserve capacity and fuel flexibility if necessary.

With these considerations in mind the S.S.E.B. decided to go ahead with their statutory submissions under the provisions of the Electric Light Act of 1909. Such an application is not subject to normal planning procedure although the local planning authority, at that time Renfrew County Council, welcomed the proposals. The plans related to a four flue, single stack station, consisting of three 660 MW generating units which could be extended to four such units at a later date, giving a potential capacity of 2640 MW, similar to that of Longannet. Part of the site's 150 acres was to be reclaimed using material excavated from the hillside above. Some 2.5 million tonnes of fuel oil would be consumed annually of which the sulphur content would not exceed 3%. At a later date this figure would be reduced to 2%. In view of the issues involved the Secretary of State decided at very short notice to hold a Public Enquiry into the proposals. Only four weeks notice of this was given during which 126 objections were lodged. This may seem a relatively small number, particularly in relation to the 20,000 which the Hunterston Inquiry attracted a few years later. But it should be emphasised that this number was a reflection of the short notice given by the Secretary of State rather than the degree of antipathy which the proposals engendered.

Objections, though rather hastily formulated, fell into two broad categories. Firstly there were those concerned with the loss of amenity which the physical presence of the buildings, and more importantly its stack, entailed in an area of widely acknowledged scenic value. Secondly, more technically orientated questions were raised as to the environmental damage which such a development involved both to local and more distant communities. It was in this second category that the questions of air pollution were considered. Both aesthetic and scientific questions are, however, closely interrelated and should be considered in greater depth. Both of these questions will now be considered with the experience of hindsight, where possible, in order to assess the wisdom of the ultimate decision to proceed.

15.2 Loss of Visual Amenity

During one of many studies of potential industrial development sites in the area Professor Arnold Weddle (1969) gave a formal analysis of the components contributing to the outstanding landscape quality of the Estuary. These characteristics included:

> " a large number of varied and readily accessible viewpoints from which good prospects can be obtained,
>
> views framed by rocks, trees and other features,
>
> man-made elements generally very much subordinate to the scale of the scenery,
>
> close foregrounds of shore, farm and parkland containing a modest number of attractive buildings,
>
> views of farmland with a mixture of pastoral and tillage economies; hedges; buildings, screened or with backgrounds of sheltering trees,
>
> middle distance margins of water with boats, buoys, piers, groynes, waders and gulls,
>
> an abundance of edges where one kind of landscape gives way to another,
>
> interplay of light, especially light which is reflected even in dull weather, and sometimes remarkably brightly in locally overcast conditions, from water surfaces which change in their reflective quality with every minor variation of weather and tide,
>
> distant prospects of islands,
>
> views of ferries, tugs, dredgers, coastal and seagoing shipping,
>
> reasonable sunshine periods to give at least a fair sample of fine weather and smiling prospect, but combined with light or broken cloud and a breeze which ripples the water and gives scudding cloud shadows,
>
> varied and not too distant backgrounds, of steep and broken topography, forests, moorland and hilltops on a bold scale. "

These then were the features which in combination produced a landscape of outstanding scenic and recreational value and sustained a tourist economy worth over £100M per annum. In the objectors' viewpoint all of these facets would be severely undermined by industrial development on this scale, particularly at the location chosen. Further support for their argument was already available from the source mentioned above (Weddle, 1969) who had continued his assessment of scenic qualities thus:

> "The most intricate and generously abundant grouping of these (above mentioned) qualities can be noted in the fine stretch from Little Cumbrae Island to Cloch Point, with perhaps a peak of value occurring in the vicinity of Wemyss Bay."

Professor Weddle had produced one of two reports commissioned by the Clyde Estuary Development Group the year previous to the Public Enquiry. This group was representative of all the local planning authorities in the Estuary. Weddle's report was accompanied by a similar one from the Metra Consulting Group Ltd. who did not share his conclusion regarding the unsuitability on environmental grounds of the Inverkip site. The advantage of low cost cooling water was their main reason for favouring the site although the existence of a suitable rock foundation behind the shoreline was also stressed.

One of the main concerns of the objectors was the visual intrusion of a tall chimney which would be visible from many parts of the estuary. Until only two weeks before the Public Enquiry a chimney identical to that at Longannet was planned. This was to consist of a four flue structure some 183m high surrounded by a concrete windshield. It was only within the two weeks prior to the Enquiry's commencement that the objectors learned of new proposals to increase the chimney height to 240m making it one of the tallest stacks in Europe and considerably increasing its visual intrusion on the landscape.

Some idea of the size of the structure can be seen in Plate 3 which shows it in relation to the main boiler house building, itself over 60m high. Of more interest however is the high degree of visibility of the stack from many locations on the Estuary. Fig. 15.1 shows a map based on

Plate 3

Inverkip Power Station

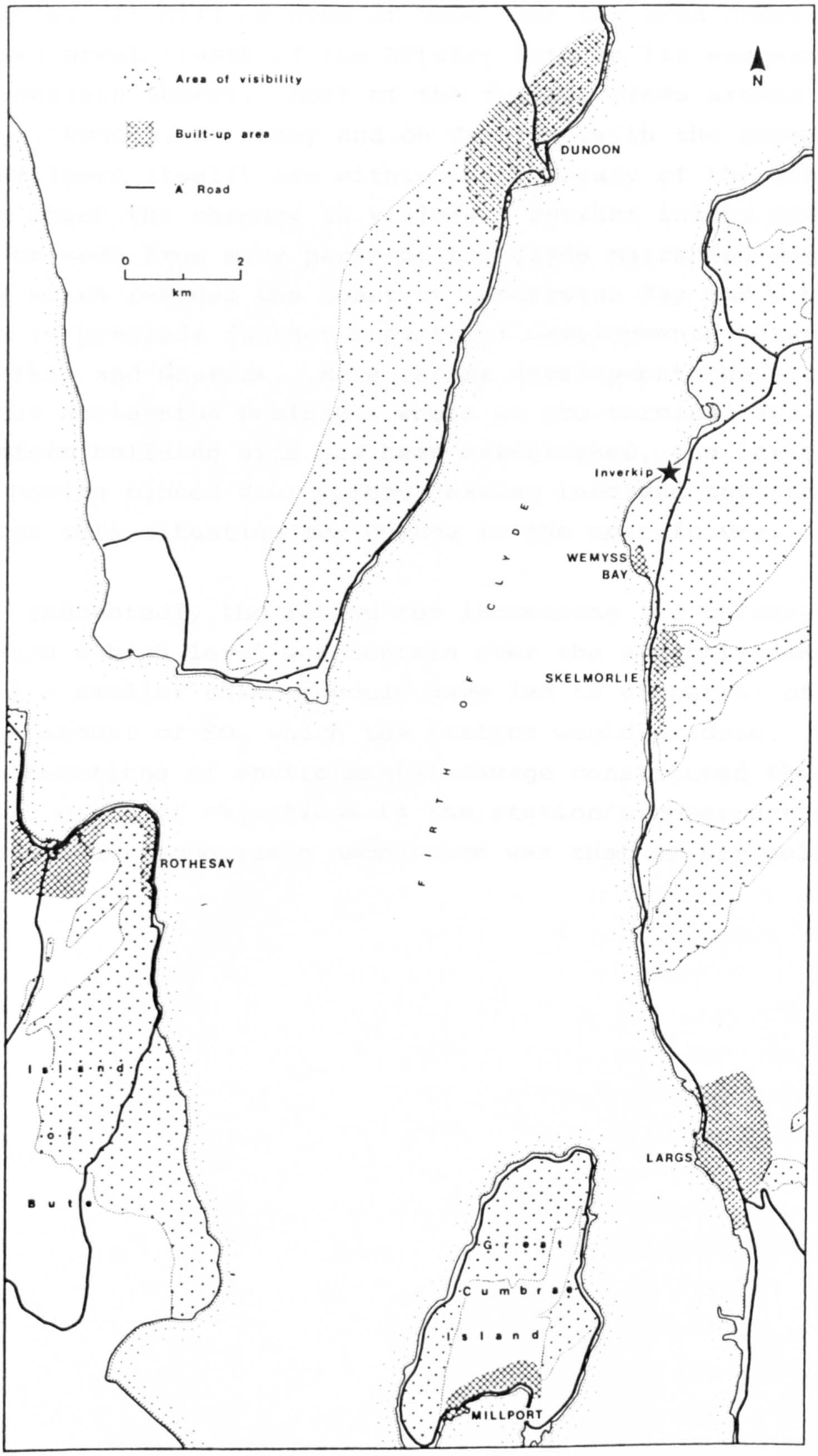


Fig. 15.1 Visibility Range of Inverkip Chimney Stack

fieldwork showing the areas from which the chimney is visible. It will be seen at once that the area encompasses great tracts of the Estuary both on its eastern and western shores. Most of the tourist areas around Largs, Dunoon, Rothesay and on Cumbrae (with the exception of Millport itself) are within the boundary of the areas from which the chimney is visible. Further inland the stack can be seen from many parts of the Clyde Muirshiel Regional Park which reaches the coast at Lunderston Bay and would seem to preclude further industrial developments between Inverkip and Gourock. More recent developments have centred on the Hunterston Peninsula where an ore terminal and oil platform building site has been established, the latter now having closed down without having received any orders, though this situation may change in the near future.

Undoubtedly the reason for increasing the chimney height to such a high level was concern over the effectiveness with which a smaller chimney would have led to dispersal of the large amount of SO_2 which the station would produce. These considerations of environmental damage constituted the second group of objections to the station's construction. Of paramount importance among them was that of air pollution.

15.3 Air Pollution Effects : Nonhebel's Report

Operating continuously at full capacity the sulphur dioxide emission rate for Inverkip will amount to about 7.5 kg/sec or some 650 tonnes/day. This is over ten times the comparable figure for Braehead power station, the only other major source of the pollutant in the vicinity. In view of such a considerable increase in the emission of SO_2 it was inevitable that concern should be expressed regarding any adverse health consequences which might ensue if the station was constructed, and this was the basis of many of the objections at the Public Enquiry. In anticipation of this the S.S.E.B. retained the services of Dr. Gordon Nonhebel, a distinguished fuel technologist with extensive experience in air pollution matters, to advise them on the containment of the emissions to limits at which no hazard would exist.

Nonhebel (1969) initially decided that this objective could best be realised by a control policy based on high stack dispersal. Only one alternative to this existed at that time. This consisted of washing the boiler flue gases in a solution of lime, thus neutralising most of their SO_2 content. Such a process had been used in two London power stations, Bankside and Battersea for a number of years, the only removal process in full commercial use. The chief disadvantage, however, lies in the fact that the gases leave the chimney cooled almost to the ambient level and saturated with water vapour. Lacking its former thermal buoyancy this steamy plume falls to ground level a short distance from the station. Such a process would not be acceptable at Inverkip where the station is overlooked by a large area of upland to the east. Wind tunnel experiments also suggested that even with a moderately tall stack of 183m and 'normal' heated effluent the effect of this high ground in the vicinity might still lead to downwash locally and on this basis Nonhebel concluded that a particularly tall stack was required, some 240m above sea level.

The figure of 240m was also based on the results of calculations of ground level concentrations of SO_2 at various locations, which, because of their distances from the chimney and elevation above sea level, necessitated special attention to ensure excessive pollution levels were not observed under certain meteorological circumstances. This involved calculating the plume rise due to buoyancy and its subsequent dispersion by eddy diffusion downwind.

In calculating plume rise Nonhebel utilised the findings of an extensive research programme based at Tilbury Power Station in London some two years earlier. An extensive series of lidar measurements of plume rise during this project suggested that the plume rise (Z max) could best be given by the expression

$$Z_{max} = \frac{\alpha Q^{1/4}}{U}$$

where α is a constant related to stack height and is of the order of 400-600 (m^2 sec $^{-1}$ MW $^{-1/4}$), Q is the heat content of the emissions (MW) and U is the windspeed (m/s).

Using such an expression in conjunction with the critical windspeed of 10m/sec Nonhebel estimated the plume rise under such conditions as 238m giving an effective chimney height of 478 metres.

In the absence of any downwash, communities in the immediate vicinity of the chimney, such as Wemyss Bay and Skelmorlie would be unaffected by the plume under all conditions excepting return from more distant localities. Areas such as Larkfield and Long Craig near Greenock and Ravenscraig Hospital would however be close to the point of maximum concentration under certain conditions and these places were more closely examined. The worst combination of weather circumstances produces a concentration of 250 $\mu g/m^3$ on an hourly basis at Larkfield with rather lower values for the other two places (Fig. 15.2). It will be seen that allowance in these calculations has been made for elevation. This is because the effect of the local topography in lifting the plume has been considered and thus the plume height used in

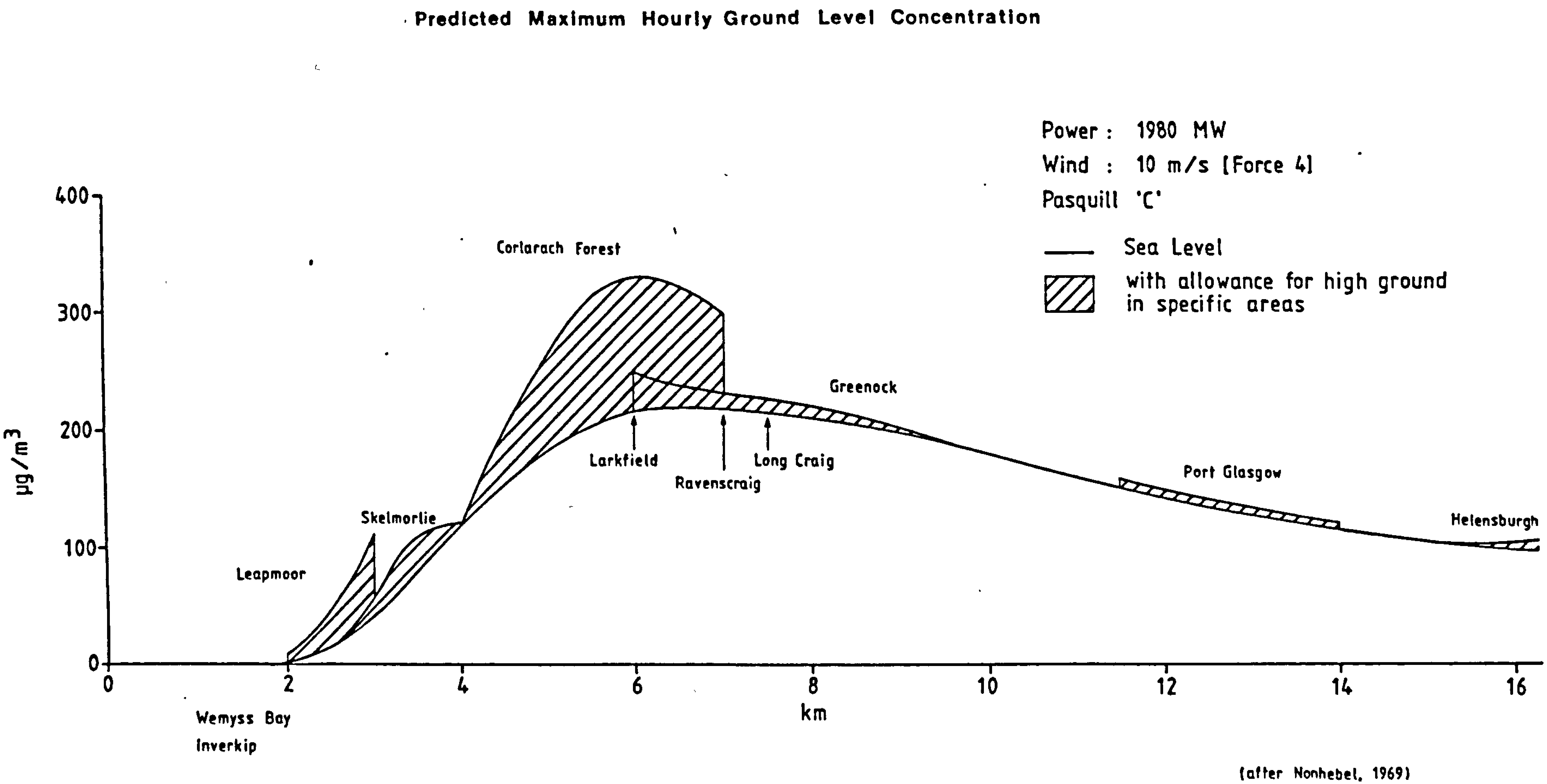


Fig. 15.2 Predicted Maximum Hourly Ground Level Concentrations

the calculations consisted of chimney height plus plume rise over chimney top plus plume uplift by rising ground less height of base level above sea level.

The worst maximum ground level concentration was found to occur at Larkfield with a wind speed of 10m/s at the top of the stack (about 5 m/s at the standard observation height of 10 m) and stability conditions corresponding to Pasquill Category C. Analysis of the directional wind data and speed data from Renfrew further suggested that these conditions only occurred in combination for 0.5% of the time and in practice this figure would be further reduced since the station was most unlikely to be operating continuously at full capacity. Thus nowhere would ground level concentrations from the station exceed 300 $\mu g/m^3$ on an hourly basis, and thus the threshold of 600 $\mu g/m^3$ at which ill effects become apparent would not be approached.

Finally Nonhebel considered the alternative sites already mentioned for the power station. With the exception of Ardgowan, in relation to none of these alternatives was there a comparable location to Larkfield where such high contributions to ground level concentrations might be expected. The amelioration was however only of the order of 20% and this was not considered significant. Hunterston was considered less favourable due to the potentially high industrial cluster which may develop there and cause concentrations in excess of 600 $\mu g/m^3$ on an hourly basis at Fairlie. Similar concentrations might also result if the station was constructed at Dundonald where airfield restrictions would limit chimney heights to 165m.

These, then were the conclusions and recommendations made by Nonhebel. It is interesting to re-examine them at this point in the light of the earlier results of this study to re-assess their validity and further demonstrate the utility of the present study.

15.4 A Critique of Nonhebel's Report

The calculation of maximum ground level concentration in neutral conditions was found in the Tilbury experiment (Moore, 1967) to be most accurate when a form of Pasquill's (1962) equation was used as follows:

$$\hat{C}_m = \frac{2Q_s}{e \; \pi \; (h_c + Z_{max})^2 \; U}$$

where $\hat{C}_m$ is the maximum ground level concentration, Q_s is the source strength (m^3/sec at n.t.p.), h_c is the height of the chimney, Z_{max} is the plume rise and U is the critical wind velocity at stack height. It will be seen at once that this concentration quantity is very suspectible to changes in Z_{max}. For this reason the calculation of plume rise is central in any air pollution impact report such as that by Nonhebel.

Using a heat output of 307 MW Nonhebel uses the Lucas (1963) formula to obtain a maximum plume rise under neutral conditions, and a 10 m/s wind at the chimney top, of 238 m, making an effective chimney height of 478 m. Keddie, on the other hand, in a later study (Keddie and Williams, 1974) used a heat output of 222 MW to obtain a larger plume rise of 280 m under the same conditions using a slightly different variant of the same formula (Lucas et al, 1970). If the Concawe formula (Brummage, 1968) is used with these two heat outputs, values of 268 m and 228 m respectively are obtained further suggesting that estimates of plume rise are subject to wide variations depending on the parameters and the formulae chosen. In such circumstances the effective chimney height of Inverkip can best be considered as lying in the range 430m - 520m implying that the concentrations utilised in Nonhebel's findings are subject to an error margin of approximately ± 20%.

Peak concentrations of SO_2 are shown in the report to occur between 6 and 8.5 kilometres from the station when Pasquill stability category C accompanies a force 3 (7-10 knots) wind or with category D and a force 4

(11-16 knot) wind. Concentrations in excess of 250 $\mu g/m^3$ on an hourly basis will be observed on such occasions in the vicinity of Larkfield to the south west of Greenock. This occurs only when the above weather conditions combine with the appropriate wind direction of 210°, an event which occurs infrequently, on average about 0.5% of the time. This reasoning is based on stability data for Renfrew published by the Meteorological Office (Met. Office Investigation Division Memoir 88) which suggests that Category C conditions occur for 13% of the time and Category D for 36% of the time. Analysis of stability conditions at Abbotsinch during the study period suggests however that these figures may underestimate the occurrence of these stability categories. Using the previously described computer programme 'Stabwind' values of 18% and 48% were obtained for these categories.

It can also be postulated that relief influences would funnel a greater spread of wind directions up the Kip Valley than the 10° used by Nonhebel. Accordingly, the relative frequencies to be used in the calculations should relate to the sector 200-220° rather than the narrower sector implied in Nonhebel's calculations. Again utilising the data on file from Abbotsinch the frequency of occurrence of force 3 winds in the sector 200-220° was found to be 2.77% and the comparable value for force 4 winds was 3.24%. This means that the frequency of occurrence of peak pollution can be calculated thus:

	% Time 200-220°	% Time Pasquill		% Combination
Force 3	2.77	C 18	=	0.50
Force 4	3.24	D 48	=	1.56
				2.06

This figure is over four times that suggested by Nonhebel and means that concentrations in excess of about 250 $\mu g/m^3$ will be observed at Larkfield for over 2% of the time. This would be equivalent to an addition of between 5-10 $\mu g/m^3$ to annual average concentrations, although given the low frequency of occasions when full station capacity coincides with these weather conditions this figure is unlikely to be realised in most years. Nevertheless, it should be noted that, in any given year, such occasions may, once established, prove persistent and produce frequencies 3 or 4 times the value above. Furthermore, examination of unpublished data from Rothesay, Gourock, Millport and Hunterston suggests that these weather conditions are more prevalent in the area than the figures from Abbotsinch suggest and the actual average for Inverkip may even be slightly higher than that mentioned above.

Perhaps the most serious deficiency in Dr. Nonhebel's report, however, is his neglect of anticyclonic conditions, in particular occasions when temperature inversions close to the top of the plume exert significant controls on ground level concentrations. He correctly discounts the influence of surface based nocturnal inversions, the most intense of which will not trap such a buoyant plume. However, inversions occurring at higher altitudes are much more significant influences on ground level concentrations. It has already been demonstrated that the existence of a temperature inversion does not affect either the critical windspeed or the downwind distance of the point of maximum concentration. However, it has been noted that a doubling of this concentration can occur when the plume rise is just up to the inversion layer. For distances beyond the position of maximum concentration the ratio between trapping and coning dispersion steadily increases, resulting in the possibility of fumigation many tens of kilometres downwind. Nonhebel was unable to obtain data on the heights and persistencies of these features. These are now available. Table 15.1 shows the number of inversions occurring in each 100m height category from 1971 to 1977. The data relates either to Long Kesh or Shanwell 12.00 ascents depending on the wind direction (see Chapter 8). The height range relevant to the Inverkip plume is probably that between 400 and 500 metres. An inversion in this height range would have the maximum effect on ground level concentrations. It can be seen that such conditions occurred on 47 occasions during the six year period, equivalent to an average of 2.15% of the time. Thus, for 2.15% of the year ground level concentrations at the point of the maximum

Table 15.1 Inversion Occurrences 1971-1977

Altitude	No. of Occurrences
0- 100m	32 (i)
100-200m	119 (i)
200-300m	62
300-400m	58
400-500m	47
500-600m	50
600-700m	58
700-800m	61
800-900m	49
900-1,000m	72

(i) Not including surface based inversions, but probably affected by them concentration (6 - 8.5 kms downwind) will be greatly enhanced to approximately twice their value in the absence of any inversion. For Larkfield this is not too serious, since south westerly winds and inversions tend to be mutually exclusive. On the rare occasions however when this is not so, and an inversion at 400-500 metres coincides with a wind direction of 200-220^{o}, hourly concentrations of 500 $\mu g/m^3$ or 3 minute values of 1,500 $\mu g/m^3$ could be expected at Larkhall.

More importantly, however, the critical distance range also encompasses Dunoon on the western side of the Firth on a bearing of 320^{o}-350^{o} from the station. Nonhebel makes no mention of Dunoon, or indeed of any location on the western side of the estuary with the exception of Corlarach Forest. This is most unfortunate since it is with a light easterly or south easterly wind that inversions in the height categories mentioned above are most likely to occur. The potential thus exists for the most severe short term effects from the power station to be experienced not to the north east in association with the prevailing south westerlies, but rather to the north west and west where the combination of wind direction, speed and inversion height may well produce circumstances conducive to high ground level concentrations.

It will be recalled from Chapter 13 that this study has investigated other mechanisms operating on a more local scale which further exacerbate high pollution episodes. This is of relevance to the circumstances to be experienced in these areas.

The influence of katabatic winds in contributing to the formation of conditions favourable for high pollution episodes was noted in Chapter 13 where it was seen that under intense anticyclonic conditions cold air drainage from the high moorlands enclosing the Glasgow Basin resulted in the trapping and fumigation of plumes which would otherwise be dispersed at higher levels. Such circumstances can also be envisaged for the Inverkip plume. Summit levels in the Renfrew Heights are of the order of

400-450m, quite similar to the plume rise figures given earlier for a 10 m/s wind in neutral conditions. It must be remembered, however, that a stack height wind speed of 10 m/s corresponds to one of only half this magnitude at the standard height of 10m and these values are frequently found in anticyclonic weather with easterly or south easterly winds. The radiation nights associated with such weather would be particularly conducive to the enhancement of the katabatic wind regime on the west facing slope of the Renfrew Heights. Thus it is feasible that a downhill flow of air towards the Firth of Clyde would become established. Such a flow would be further reinforced by land-sea temperature contrasts in winter, particularly when the hills are snow covered, and a marked subsidence of air on the eastern side of the Firth may be observed. This would have the effect of restricting the dispersal of the Inverkip plume, dragging it prematurely down to sea level where it would be slowly transported across to the western shore, causing greatly enhanced values in its largely undispersed state.

Under stronger easterly winds plume rise would match even more closely the general elevation of the surrounding hills. At this point maximum rise plume buoyancy would be almost neutralised and the plume would be almost totally under the control of the prevailing wind conditions. Crowe (1971) has described how, under such circumstances, air descending from a higher level may set up an eddy in its lee. As a result of this he noticed that in parts of the English Lake District the precipitation amounts on the lee side of a trough were often, in cross wind conditions, equal to, or even in excess of those measured on the more exposed windward side. The production of such a 'roller' in the Firth is likely under the conditions described above when a brisk easterly wind is blowing. This would also result in the plume being brought down to sea level in the falling component of this cell on the western side of the Firth.

Fig. 15.3 shows the two possibilities discussed above, conditions which are particularly relevant for locations such as Dunoon, Innellan, and with a north easterly wind,

TWO POSSIBLE SCENARIOS FOR GREATLY ENHANCED SO_2 CONCENTRATIONS AT DUNOON

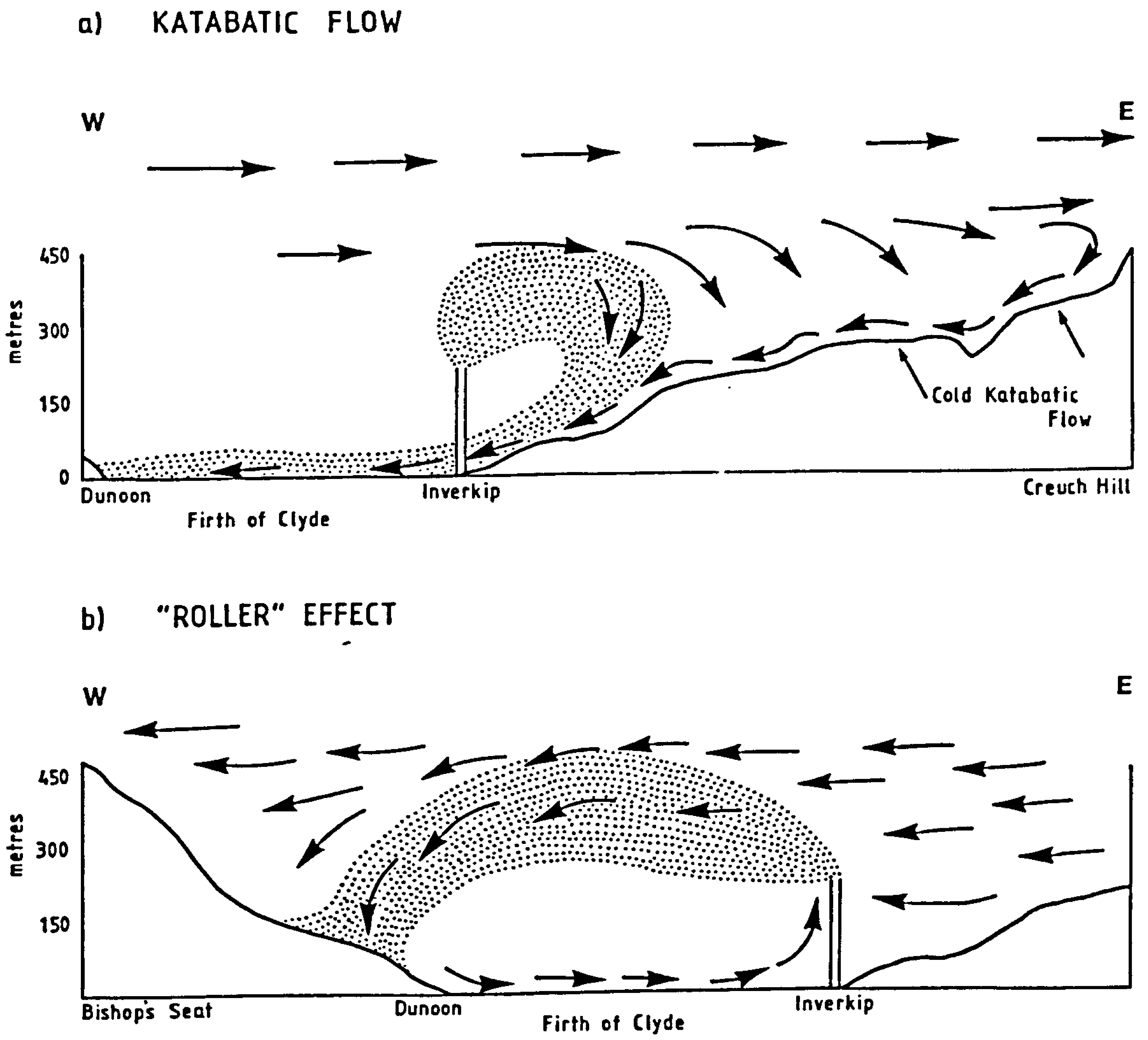


Fig. 15.3 Two Possible Scenarios for Greatly Enhanced SO_2 Concentrations at Dunoon

Rothesay. Concentrations well in excess of those predicted by Nonhebel can be expected on such occasions. Table 15.2 suggests that north easterly winds are observed at Rothesay at least 7.2% of the time, of which force 3 or 4 probably occurs about half of this time. No such data exist for Dunoon where much greater peak concentrations can be expected due to the distance relationships described earlier, Dunoon being equidistant with Larkfield from the stack.

Mention should also be made of conditions below a trapping inversion at about 400-600 metres. The air below this can be stable, inhibiting lateral dispersal, or unstable and tending to rise. The lateral dispersal of a coning plume can be calculated according to a formula utilising coefficients evolved by the Tennessee Valley Authority. This is given by

$$\sigma_y = cx^d$$

where

σ_y = lateral dispersion

x = downwind distance

and c and d are constants as follows:

	Neutral	Stable
c	0.37	0.78
d	0.76	0.63

At the critical downwind distance of 8 kms σ_y, the crosswind deviation, = 342 metres in neutral conditions, but only 224 metres in stable conditions. This is before the vertical dispersion parameters are even considered and indicates that, in addition to the doubling of concentrations which the inversion would produce, a further enhancement due to constraints on lateral dispersal may be expected when stable conditions prevail below the inversion.

If, on the other hand, the lapse rate below the inversion is unstable equally serious consequences may occur. With an easterly flow leaving the relatively cool land for the relatively warm waters of the Firth during winter some element of surface heating of the lower levels is inevitable. This would render the lower layers of air unstable, setting up convective eddies which might eventually bring down high level effluent trapped below the base of the inversion. It has already been shown how a similar process occurs when daylight stirring of a polluted airmass occurs (Chapter 4). The fumigation which this entails would certainly produce short periods of intense pollution, perhaps giving 3 minute values at Dunoon in excess of 2,000-3,000 $\mu g/m^3$.

It is thus clear that the impact of Inverkip on SO_2 concentrations at populated areas in its vicinity is very much greater than that postulated by Nonhebel. The evidence is based on a detailed knowledge of the micro climate of the Firth of Clyde and on the conclusions drawn concerning meteorological influences on the dispersal of effluent in such an area, considering the very important effects of relief which are apparent. In this context the objectives mentioned by Professor Weddle in Chapter 1 have been satisfied.

15.5 A Postscript on Concentrations at Linwood under Westerly Winds

Pollution emanating from Inverkip might be expected to be detected on occasion through much of Central Scotland, in the same way as the effects of Longannet were detected in Chapter 11. During the six year study period to which most data related, however, only intermittent operation of part of the planned output occurred, largely associated with trials and commissioning of the boilers of the first 660 MW generating set. In the two year period from 1977 to 1979 for which additional data became available during the preparation of this thesis, the remaining two 660 MW units were commissioned. As a result of this some preliminary investigations were made into the effects of the power station, if any on the Linwood concentration data.

Using the techniques already established earlier in this study the sulphur dioxide concentrations were related to various wind directions, using the average mean vector wind as an indicator of the daily wind direction characteristics. The wind sector 270^o-300^o corresponded to the bearing of Inverkip from Linwood and values from this sector were compared with averages for the corresponding year from all wind directions.

Fig. 15.4 relates average SO_2 values for the Inverkip sector to annual averages for each year from 1971 to 1979. Clearly, increased pollution loading on the sector is apparent from 1974/75 onwards. While the sector average in 1973/74 was only 45% of the overall average SO_2 concentration, in 1978/79 it was 105%. The trend of the graph moreover appears to show some relationship to increases in generating capacity at the station. In fact even the dip apparent in 1976/77 could conceivably relate to reduced activity at the station, it being closed for some months during summer 1977 due to turbine faults, though this may be rather speculative. Certainly winds from directions 270^o-300^o appear to be more polluted than formerly. This is confirmed in Fig. 15.5 which depicts the highest daily SO_2 concentration corresponding to this direction.

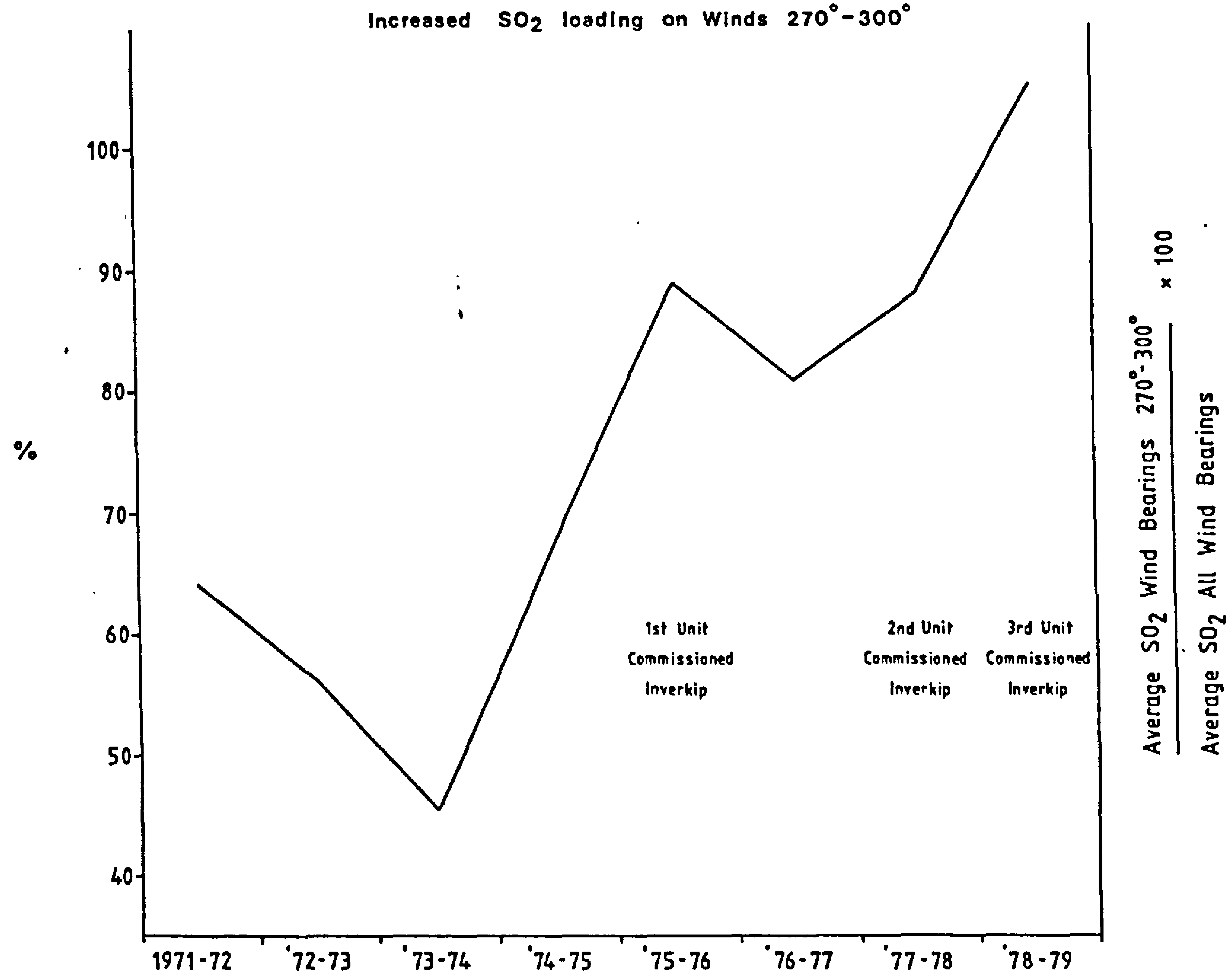


Fig. 15.4 Increased SO_2 Loading on Winds 270°-300° at Linwood

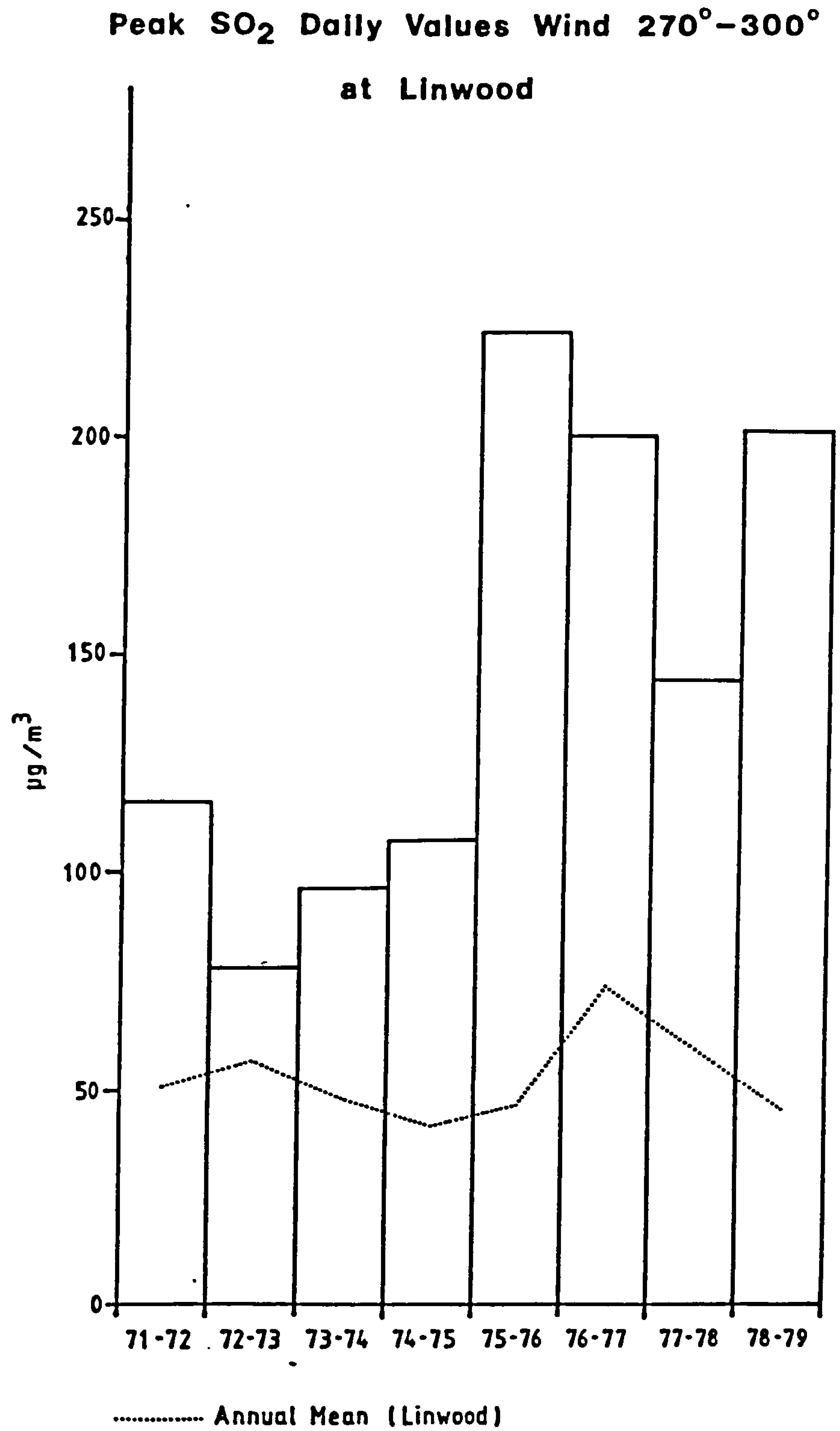


Fig. 15.5 Peak SO_2 Daily Values on Winds 270°-300° at Linwood

Peak values for the first four year period average about 100 $\mu g/m^3$; for the second four year period they are almost doubled, despite only a slight increase in overall annual averages.

It is speculative to read too much into these results at this stage, particularly as the 1977 and 1978 records at Linwood are not complete. But nevertheless these findings do suggest that the influence of Inverkip is already detectable in the Glasgow Basin. Furthermore it would appear that the ultimate impact of the station may well exceed the 5-10 $\mu g/m^3$ annual increment projected by Keddie et al in the West Central Scotland Plan, and also by Nonhebel. In these circumstances the planned extension of the station to a four unit model would require considerable further study as also would the possibility of the introduction of fuel with a sulphur content in the region of 1% if unacceptable concentrations were not to occur at the localities mentioned earlier.

CHAPTER 16

CONCLUSIONS

(Marginal figures refer to relevant sections)

It is appropriate at this point to restate the problem expressed by Weddle (1969) concerning air quality management in West Central Scotland:

> '(Investigations) have shown how difficult it is to produce concrete evidence as to the production and behaviour of pollutants from future industry. This is because the behaviour of smoke plumes and air currents taking away pollutants is affected by local topography and because a detailed knowledge of micro climate is required, which is often not available.'

This statement provides a good justification for the present study. When dissected it can be seen to define, for the area concerned, a lack of understanding of the nature of the interaction between three major controls on ground level concentrations of pollutants. This relates firstly to the influence of the relief configuration of the region, secondly to the nature and geographical distribution of present and planned sources within it, and thirdly to short and long term climatic influences on the dispersal of such emissions. These are the three foundations on which this study was constructed and it is in the context of them that conclusions are framed.

Initially, however, it is apparent that Weddle's problem was to some extent associated with the uniqueness of West Central Scotland. Indeed each of the three influences above are unique in a spatial context. No two areas have identical physical characteristics, emission distribution patterns, or climatic environments. This might imply therefore, that the conclusions to be drawn from this study have no relevance outside the region. This is not the case. While undoubtedly such findings are geared primarily towards application in West Central Scotland, basically they involve relationships between the three controls mentioned which exist to some degree wherever the atmosphere is used as a waste disposal medium. For this reason, therefore, conclusions which seem to relate only to local conditions may also be relevant when viewed in a wider perspective.

2.2 Commencing on a national perspective the problem of air pollution was seen to be one which only aroused public consciousness when its hazard potential was demonstrated in the early 1950's. Progress since then has centred on dramatic reductions in the emission of particulate matter, though some doubt was expressed on the extent to which this was attributable to legislation such as the Clean Air Acts. Changes in fuel preference by consumers and industrialists alike would seem to be at least equally responsible for a continuing reduction in ground level concentrations, a decline which may be arrested in future, at least in the short term, should coal consumption by domestic consumers rise again.

2.3 In any case, much less progress was noted with respect to sulphur dioxide emissions and the fall apparent in urban concentrations of the gas was linked to a major relocation of large sources to out of city centre locations. This was particularly marked with regards to power station location as less efficient, smaller units near to cities gave way to large new installations
3.5 on tidewater sites. West Central Scotland exemplified this trend, one which has important implications for sulphur dioxide levels over a much wider area than hitherto. Such changes naturally focused attention more on the rural and semi rural zones beyond the cities, zones in which the Renfrew Air Pollution Project sites were located.

5.1 Initial examination of this data revealed the
5.2 expected seasonal and daily cycles, and the positively
5.3 skewed frequency distributions of daily values of both smoke and sulphur dioxide concentrations. It also confirmed the existence of an air pollution problem in parts of the study area as defined by established international criteria. Examination of the data in conjunction with meteorological data, however, enabled more far-reaching conclusions as to the nature, location and dispersion of emissions both from within and outside the region to be made.

7.2 Mean concentration levels displayed a marked
sensitivity to wind direction, with a large contrast
in levels associated with winds from urban and rural areas.
When further examined, differences in source type
(area or discrete) and source characteristics (sporadic
or continuous) became apparent. For certain trajectories
individual sources could also tentatively be suggested.
This was principally the case for sulphur dioxide.
Smoke was invariably attributable to local domestic
7.3 emissions. This latter conclusion was further reinforced
when wind velocity data were examined. Smoke was seen
to be highly susceptible to dispersion by wind action,
lacking the buoyancy and coherence of sulphur dioxide
emissions, characteristically released from high stacks.
Sulphur dioxide was less prone to wind dispersal because
of this. The design characteristics of such tall
stacks were such as to retain the plume as discrete as
possible for as long as possible. This maximised plume
rise by restricting entrainment of ambient air, implying
a capability for transport, a conclusion which was to be
a recurring theme of later investigations concerned with
particular sources and conditions. Yet while these
findings agreed well with research from the U.S.A. and
U.S.S.R. a complication was noted in the existence of
double peaks on the concentration/windspeed profiles
for certain directions. Such a phenomenon was found to
be explicable as the manifestation of the merger of
two data sets, one related to more stable nocturnal
conditions and the other to more unstable daytime
circumstances. This introduced a new dimension into the
analysis, that of atmospheric stability as an important
ingredient to be considered before observed concentrations
could be explained or potential new sources appraised.

The existence of stable layers, where the normal
temperature-height lapse rate is inverted, provides
8.1 a lid on the vertical mixing of polluted air. Such layers
were found to have been associated with most periods of
enhanced pollution at many locations apart from
8.2 Central Scotland. The most common types of situation
to occur were shallow surface based inversions related

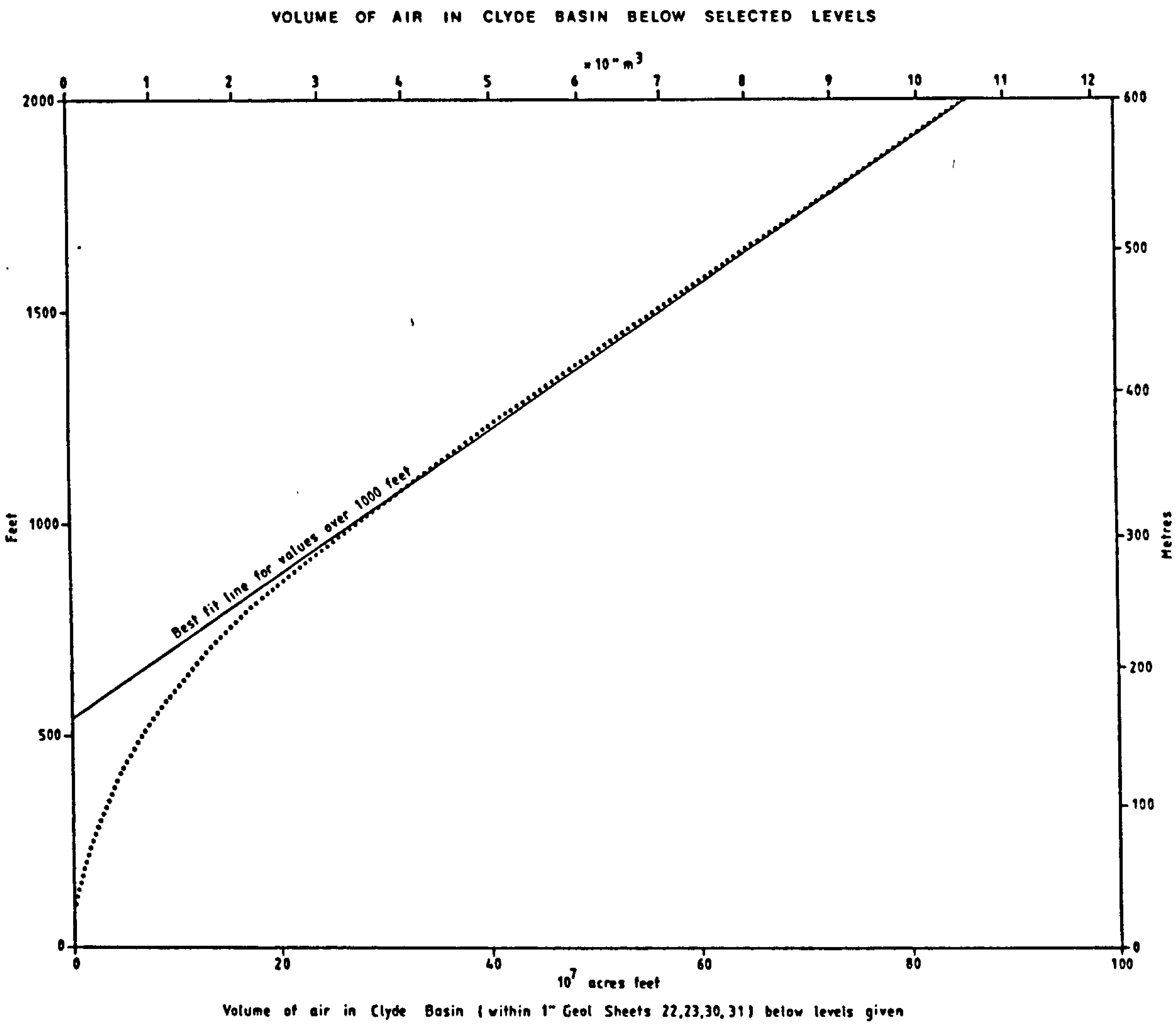


Fig. 16.1 Volume of Air in Clyde Basin below Selected Levels

to nocturnal cooling. These were observed on about half the nights over a six year period at Long Kesh and Shanwell. A slightly greater frequency was apparent at the more continental location, Shanwell, on both daytime and night-time radiosonde ascents, a reflection of the relatively greater importance of radiational rather than advectional controls at that station as
8.3 compared with Long Kesh. Such a conclusion fitted in to a pan European perspective incorporating work in West Germany (Schwegler, 1967) and the U.S.S.R. (McIntyre and Thornton, 1978). Such surface based features appeared however to have little effect in trapping pollution except where they persisted throughout the day. This was certainly not the case with their free air counterparts.

9.3 Differentiation between frontal and subsidence free air inversions suggested that the latter were the most effective trapping agents, though only at certain critical heights. Such findings confirmed the importance of a complicated interaction between the relief configuration and inversion climatology of West Central Scotland as a major determinant of ground level concentrations throughout the region. Such a relationship is implicitly suggested in Weddle's statement.

10.2 Sulphur dioxide levels were highest when an inversion was based around 300 metres, though slight differences were noted between day and night observations. This is highly significant, corresponding as it does to the principal low-level erosion surface identified by George (1958). The oscillation of the trapping lid above or below this level is thus critical in determining the volume of air throughout which pollution is mixed in the rather confined Clyde Basin. This, then, is a major conclusion of this study, namely that air pollution environmental impact analyses require to consider mixing volume rather than mixing height alone, when predicting ground level concentrations. Further vindication of the role of an inversion at about 300 metres can be seen in Fig. 16.1 which shows the volume of air in the Clyde Basin below selected levels.

Quite clearly, above about 300 metres the volume of air available for mixing pollutants expands linearly at a rate greater than that apparent at heights below this value. This means that as the trapping level rises above this height a rapid expansion in mixing volume occurs. As the trapping level falls to 300 metres and below, however, the available mixing volume diminishes at an accelerating rate. The interaction of relief and inversion height is obvious. This height of about 300-400 metres corresponds to the higher levels of the volcanic plateaux surrounding the Glasgow Basin. These are in turn overlooked by the main erosion surface of
10.3 the Highlands and Southern Uplands at about 700 metres. A secondary peak in the pollution/mixing height profile was noted when inversions lay close to this category. A stepped progression is thus apparent with further vestiges possibly in evidence at even higher levels. Nevertheless the improvement in air quality which could be anticipated in the Basin if new sources had effective chimney heights of around 400 metres is an obvious application of this conclusion.

The extent to which these level were found to enhance the effect of the trapping inversions varied with wind speed. At higher wind speeds the higher terrace levels were much more significant and were seen to be instrumental in canalising effluent into the Basin through particular relief gaps. This was most marked on easterly winds.

11.2 The funnelling of effluent through the Cumbernauld Gap under certain inversion conditions was confirmed and Longannet isolated as the most likely source.
11.3 Indeed calculations suggested that, under specific wind conditions, Longannet's plume had its maximum ground level concentration close to the Linwood monitor. That such conclusions could be substantiated at least in part from the data was rather surprising in view of the intervening location of Glasgow city with its considerable heat island effects, most marked under anticyclonic (easterly) conditions. What was equally interesting, however, was the observation that with

an inversion at about 650 metres an apparent doubling of concentrations on easterly winds occurred. This figure is not too dissimilar from the effective chimney height of Longannet under such conditions, confirming Kumar and Djurfors' (1977) contention that maximum enhancement by an inversion at the point of maximum concentration is a doubling of values, this occurring when inversion height and effective chimney height are equal. Thus inversions can be seen as critical not just in relation to relief influences, but also to source strengths for large emitters. Such a conclusion suggested further examination of the frequency and persistency of these features at various heights.

12.3 Despite the central importance of inversion persistency in, for example, forecasting air pollution potential, little research has been done in this field due largely to instrumental and definitional problems. Once these and other problems were tackled conclusions regarding inversion duration and persistency at various altitudes were possible. In particular it was found that the level between 500 metres and 1,000 metes showed a pronounced tendency for persistent inversions lasting on occasions for more than a week. Seasonal variations were also noted and could be related to the synoptic climatology of the station concerned, and in particular to the relative roles of radiation and advection controls. Inversion behaviour during periods of prolonged subsidence was carefully examined and found closely to match, in terms of rates of descent, that of one such occurrence at New York during a major air pollution episode (Holzworth, 1972). It can be concluded from this that, based on meteorological criteria, air pollution potential in the British Isles can be as great on occasion as in climatic regimes dominated by slow moving anticyclones. Inversion probabilities were calculated for various durations at selected heights. Such calculations may well have a place, alongside wind direction or stability categories in assessing the potential effect of new pollutant sources.

Inversions were closely associated with various episodes when greatly enhanced ground level concentrations of smoke and sulphur dioxide were recorded at various locations within the Basin. Dense fogs were also often in evidence on such occasions, producing daily sulphur dioxide concentrations of up to 1,000 $\mu g/m^3$ in Glasgow city centre.

13.2 Thermohygrograph data collected, and personal observations made, on the surrounding hills of the Basin suggested that such fogs often have well defined tops at altitudes of between 150 metres and 200 metres. Frequently this coincides with an inversion at this height, below which, all but the most buoyant of emissions from within the Basin may be trapped. For individual cases various models of fog development and dispersal were examined. In particular the classical theory of radiation fog behaviour as outlined by Roach et al (1976) was found to be unsatisfactory when applied to the various episodes. It was hypothesised that this was due to their neglect of the role of turbulent diffusion, in particular, katabatic drainage of cold air from the higher levels down to the valley floor. Evidence for the existence of such flows was apparent on the thermograph records. Indeed it was further suggested that previous work by Reiher (1936) might imply that the quasi periodic oscillations of fog thickness measurements observed by Roach (1976) were in fact related to rhythmic katabatic outbursts.

A search for a model of fog development based on airflow considerations as the dominant feature, rather than radiational considerations only, revealed a study by Pilie (1975) involving the extensive monitoring of
13.3 valley fogs in upstate New York. Based on the contention that valley fog formation is a result of nocturnal circulations of the type described by Defant (1951) such a model was found to explain well the principal pollution episodes observed in the Basin in association with fogs. Not only so, but pulses of downvalley winds were noted of a magnitude, in terms of depth, hitherto not fully appreciated, and as such, capable of stirring pollution downwards from

fairly low-level free-air inversions. Such a conclusion had practical application in the case of the Inverkip plume, as was later demonstrated.

14.1 Not all high pollution episodes were found to be associated with winter fogs, however. An increasing occurrence of moderately high levels of sulphur dioxide was noted in summer observations. Not only so, but such occurrences appeared to contradict many of the concentration/meteorological relationships established previously. Analysis of the data confirmed this conclusion, but also raised doubts as to the nature
14.2 of pollution measured on at least one occasion. More specifically, it was concluded that evidence existed which might suggest that for one period at least the high sulphur dioxide concentrations reflected a photochemical air pollution component. This was a rather surprising conclusion and probably represents one of the first cases of this type to be observed in Scotland. Undoubtedly, the combination of summer heatwave conditions and rising car ownership levels is primarily responsible, but perhaps one other factor can be suggested in concluding this study. That is, that there exists a climatic factor promoting an increased liklihood of photochemical air pollution in future. It was seen in Chapter 3 that smoke concentration levels have fallen dramatically in recent years, a trend which was largely responsible for improved visibility records at Abbotsinch. In can be suggested here that the increasing transparency of the atmosphere in the Glasgow Basin is conducive to creating an increased potential for photochemical reactions in the area.

14.3 Equally surprising was the conclusion that under certain meteorological conditions pollution was monitored from distant sources beyond Scotland, possibly from Merseyside. Though such conditions were rare, they nevertheless confirm one of the main conclusions of this study, namely the failure of high stacks to disperse pollutants under certain inversion conditions.

15.1 The last stage of this investigation centred on the practical application of the above conclusions to a case study, that one which Weddle was originally concerned with, Inverkip Power Station. Many of the above conclusions were highly relevant in assessing the potential impact of the station. In several respects they suggested that original estimates of ground level concentrations were too low. In particular the neglect of the role of temperature inversions was seen as highly detrimental to Nonhebel's (1969) analysis.

15.4 Situations were hypothesised where the microclimatic factors referred to by Weddle, and outlined in this study, would produce unacceptable concentrations of sulphur dioxide at populated areas on the western

15.5 side of the Firth of Clyde. Even for the more distant Glasgow Basin preliminary analysis of recent data suggested that substantial increases in sulphur dioxide concentrations emanating from the direction of the station are already occurring. Certainly any planned expansion of the station would require careful analysis in terms of air pollution impact over a wide area of Central Scotland.

Answers to a number of problems not specific to West Central Scotland can be formulated on the basis of some or all of the above conclusions. Their diversity, however, opens up other avenues of research in this field which might be profitably pursued in other studies. In particular, this might entail further extension of the work on inversion behaviour perhaps incorporating acoustic sounding data, or shorter term analysis of specific plumes utilising continuous monitoring techniques. Equally so, investigations of long distance transport both of conventional and photochemical pollutants would now seem a necessary component in most pollution studies. But perhaps it is at the local scale that the type of air pollution impact analysis conducted for Inverkip needs to become much more widespread and accessible for public scrutiny and monitoring. In this way effective management of atmospheric resources can be achieved initially on a local and eventually on a global scale. The necessity of achieving the latter is no less important for mankind as a whole than is local control for the health of the individual. Yet, the degree of international co-operation required to achieve this goal is enormous, and is unthinkable at present. Mutual self interest among nation states may well be the spur eventually in co-ordinating, sharing, and regulating the use of air, the last of the 'free' resoures.

APPENDIX A

As described in Chapter 4.3 observations of temperature and humidity were made on the north-facing slopes of the Gleniffer Braes, overlooking the Glasgow Basin, during the course of this study. These commenced in November 1975 and were of necessity prematurely terminated in May 1977 when the higher site at Gleniffer was damaged by vandalism, and the calibration thermometers stolen. During the eighteen months, weekly visits were made to both this station and that at Stanely some 150 metres downslope from Gleniffer, in order to check on the accurate functioning of the thermohygrographs, and to change the weekly chart. Observations of cloud cover, wind direction and approximate strength, and present weather were noted, as well as temperature and humidity on each occasion. The maximum and minimum thermometers were read and reset and their values marked at the appropriate point on the thermohygrograph traces. When the instruments appeared to be reading higher or lower than seemed correct an adjustment was made to the tension of the bimetallic strip. A similar running calibration was carried out on the humidity records using the wet and dry bulb thermometers also housed in the screen. Of course both instruments had previously been checked against each other by being run in the same screen for a time prior to their locations on the hillside.

The network had been established to provide a local data base which might bridge the altitudinal gap between the surface observations at Abbotsinch and the more distant upper air observations from Shanwell and Long Kesh. Intuition suggested, and subsequent events further strengthened this, (Ch. 10.3), that trapping inversions may have occurred in the Glasgow Basin which were not apparent on the radiosonde data. For this reason a local data source for the lower levels of the atmosphere was considered desirable for the Glasgow Basin. Such a source of information, it was hoped, might stand comparison with that of the two radiosonde stations, at least for altitudes up to about 300 metres O.D.

It must be admitted that this objective was never fully achieved, and, indeed, the utility of the observational records in general was less than hoped for. The reasons for this are many, but it is perhaps worth documenting a few which may prove useful to other workers contemplating a similar exercise.

It will be recalled that the location of the Stanely screen was not chosen according to meteorological criteria, but in part reflected security considerations and a desire to reduce the oscillations on the trace caused by katabatic drainage of cold air down the slope. The shelter provided by an adjacent 1.5 metres wall upslope achieved both these objectives, but meant that a considerable contrast in the degree of exposure existed between this instrument and those at Abbotsinch and Gleniffer. This made comparison of the traces difficult and raised a question as to what extent conditions at Stanely were representative of those at that altitude. By contrast the hilltop location may even have been over exposed with no vestige of shelter within a mile radius of it.

More tangible difficulties, however, existed with the instruments themselves. Even when calibrated accurately they displayed different sensitivities to changes in temperature, one showing a good daily oscillation of temperature where the maximum and minimum were not far removed from the mercury and alcohol thermometers, the other displaying a narrower, rather damped, curve which made inversion measurements rather tenuous on occasion. Despite constant maintenance their performance continued to display such variations and this seemed to be due to constructional differences, however slight.

Maintenance was necessary throughout the period and a third instrument was constantly kept calibrated in the large screen for such eventualities. The most common fault was one of friction in the pen assembly which caused the pen to move in a series of jumps following a temperature change rather than react smoothly. On such occasions the instrument was removed, dismantled and cleaned and the bearings lubricated with graphite. It was then recalibrated in the large screen before being put back into service.

The existence of two instruments in the large screen, both carefully calibrated, often produced two charts which differed one with the other over parts of the week long period and agreed exactly for the remainder. On occasion differences between the two traces from the one screen were larger than those between the two sites. In such circumstances it was rather speculative to draw firm conclusions concerning reduced lapses or periods of inversion.

It should not be concluded however that these difficulties rendered the fieldwork completely unproductive. Visual interpretation of the records has produced a data base which can be considered a useful record of short term changes in temperature and humidity for the three stations. Synoptic features such as fronts are particularly clear and local influences such as katabatic winds are also apparent. The principal utility of the programme it must be concluded lay in the valuable information it gave in connection with periods of enhanced pollution in the Basin. This was clear from Chapter 13 where the relationships between pollution, temperature structure, and air movement were strikingly demonstrated. For this alone the establishment and maintenance of the thermohygrograph network can be considered a worthwhile exercise in fieldwork.

BIBLIOGRAPHY

Absalom, H.W. (1954). Meteorological Aspects of Smog. Quarterly Journal of the Royal Meteorological Society 80, 261-266.

Air Ministry (1950). Memorandum on the Requirements of a Climatological Station, Meteorological Office, London.

Ardsol, M.D. et al (1964). Reality and the Perception of Environmental Hazards. Journal of Health and Human Behaviour 5, 144-153.

Attwater, M. (1970). Planetary Albedo Changes Due to Aerosols. Science 170, 64-66.

Bach, W. (1972). Atmospheric Pollution. McGraw-Hill, New York.

Baker, D.G. and Enz, J.W. (1969). Frequency, Duration, Commencement Time and Intensity of Temperature Inversions at St. Paul-Minneapolis. Journal of Applied Meteorology 8 (5), 747-753.

Ball, D.J. (1976). Photochemical Ozone in the Atmosphere of Central London. Nature 263, 580-582.

Barnes, R.A. (1975). Transport of Smoke and SO_2 into Rural Areas of England and Wales. In : Hey, R.D. and Davies, T.D. (Eds.), Science, Technology and Environmental Management, 165-179, Saxon House, London.

Barnes, R.A. and Eggleton, A.E. (1977). The Transport of Atmospheric Pollutants across the North Sea. Atmospheric Environment 11, 879-893.

Beaver, H. (1958). Committee on Air Pollution Report. H.M.S.O., London.

Bergeron, T. (1928). Uber die dreidimensional verknüpfende Wetteranalyse. Geofysiske Publikationer 5, No.6 (Oslo), 111.

Bjerknes, J. and Solberg, H. (1922). Life Cycle of Cyclones and the Polar Front Theory of Atmospheric Circulation. Geofysiske Publikationer 3, No.1 (Oslo), 18.

Borisov, A.A. (1965). Climates of the U.S.S.R. Translated : R.A. Ledward. Oliver and Boyd, Edinburgh.

Bower, J.S., Maughan, R.A. and Roberts, G.H. (1979). Survey of Air Pollution in the Eastern Strathclyde Region : An Analysis of the First Five Months' Data. Scottish Development Department, Edinburgh.

Breeding, R.J. et al (1975). The Urban Plume as seen at 80-120km. by 5 Different Sensors. Journal of Applied Meteorology 14, 204-216.

Bringfelt, B. (1971). Important Factors for the sulphur dioxide concentration in Central Stockholm. Atmospheric Environment, 5, 949-972.

British Standards Institution (1969). Methods for the Measurement of Air Pollution. Part 2. Determination of Concentration of Suspended Matter. British Standards Institution, BS1747 Part 2. Part 3. Determination of Sulphur Dioxide. British Standards Institution, BS1747 Part 3, London.

Brodine, V. (1971). Air Pollution. Harcourt Brace Jovanovich Inc., New York.

Brown, R. and Roach, W.T. (1976). The Physics of Radiation Fog : II - a numerical study. Quarterly Journal of the Royal Meteorological Society 102, 335-354.

Brummage, K.G. (1968). Calculation of Atmospheric Dispersion from a Stack. Atmospheric Environment 2, 197-224.

Bryson, R.A. (1973). Drought in Sahelia, Who or What is to Blame? Ecologist 3, 366-371.

Bryson, R.A. (1974). A Perspective on Climatic Change. Science 184, 753-760.

Budyko, M.I. (1970). Comments. Journal of Applied Meteorology 9, 310.

Burton, I., Kates, R. and White, G. (1978). The Environment as Hazard. Oxford University Press, New York.

Carnow, B.W. (1971). see Brodine, V. (1971). A Special Burden. Environment 13 (2), 22.

Carpenter, S.B. (1971). Principle Plume Dispersion Models. Journal of the Air Pollution Control Association 21, 491-495.

Chalmers, A.K. (1930). The Health of Glasgow 1818-1925 : an outline. Corporation of Glasgow, Glasgow.

Chandler, T.J. (1961). The Changing Form of London's Heat-Island. Geography 46, 295-307.

Chandler, T.J. (1962(a)). London's Urban Climate. Geographical Journal 128, 279-302.

Chandler, T.J. (1962(b)). Diurnal, Seasonal and Annual Changes in the Intensity of London's Heat Island. Meteorological Magazine 91, 146-153.

Chandler, T.J. (1964(ä)). City Growth and Urban Climates. Weather 19, 170-171.

Chandler, T.J. (1964(b)). An Accumulated Temperature Map of the London Area. Meteorological Magazine 93, 242-245.

Chandler, T.J. (1965). The Climate of London. Hutchinson and Co., London.

Chandler, T.J. (1967). Night-time Temperatures in relation to Leicester's Urban Form. Meteorological Magazine 96, 244-250.

Chandler, T.J. (1971). Selected Bibliography on Urban Climates. World Meteorological Organization No. 276.TP.155. W.M.O., Geneva.

Chorley, R.J. and Haggett, P. (Eds.), (1969). Physical and Information Models in Geography. Methuen, London.

Clarke, J.F. (1969). Nocturnal Urban Boundary Layer over Cincinnati, Ohio. U.S. Monthly Weather Review 97, 582-589.

Clifton, M. et al (1959). The Reliability of Air Pollution Measurements in Relation to the Siting of Instruments. Int. Journal of Air Pollution 37, 6-12.

Cohen, B.L. (1977). The Disposal of Radioactive Wastes from Fission Reactors. Scientific American 236, 21-32.

Comer, P.J. (1976). The Air Pollution Meteorology of West Central Scotland. M.Sc. Thesis, University of Strathclyde.

Commission of the European Communities (1977). State of the Environment : First Report. E.E.C. Commission, Brussels.

Cox, R.A., Eggleton, A.E., Derwent, R.G., Lovelock, J.E., and Pack, D.H. (1975). Long Range Transport of Photochemical Ozone in North Western Europe. Nature 255, 118-121.

Crowe, P.R. (1971). Concepts in Climatology. Longmans, London.

Curran, J.C. et al (1977). Cairngorm Summit Automatic Weather Station. Weather 32 (2), 61-63.

Defant, F. (1951). Local Winds. In : American Meteorological Society, Compendium of Meteorology, American Meteorological Society, Washington.

Dickens, C. (1853). Bleak House. Chapman and Hall, London.

Djurfors, S.G. (1972). Relative Importance of Initial Velocity and Buoyancy of Chimney Gases. Ontario Hydro Research Quarterly 24, 6-10.

Douglas, J.W. and Waller, R.E. (1966). Air Pollution and Respiratory Infection in Children. British Journal of Preventive and Social Medicine 20, 1-8.

Dworkin, J. (1974). Global Trends in Natural Disasters 1947-73. University of Colorado, Institute of Behavioral Science N.H.R.W.P. No.26.

Edelman, S. (1968). Air Pollution Control Legislation. In : Stern, A.C., Air Pollution 2nd Ed. Vol. 3, Academic Press, New York.

Elsom, D.M. (1976). Meteorological Controls Upon Ground Level Concentrations of Smoke and Sulphur Dioxide in the Manchester Area. Paper presented at the Association of British Climatologists meeting, Institute of British Geographers Conference, Coventry, Jan. 6th-10th.

Evelyn, J. (1661). Fumifugium, London.

Ewing, P.H. (1972). Potential Relief from Extreme Urban Air Pollution. Journal of Applied Meteorology 11, 1342-1345.

Farman, J.C. and Thom, A.S. (1970). Ben Nevis Observatory : a plaque unveiled. Weather 25, 77-82.

Ferrel, W. (1856). An Essay on the Winds and Currents of the Ocean. Nashville Journal of Medicine and Surgery 11 (4), 287-301.

Forsdyke, A.G. (1970). Meteorological Factors in Air Pollution. World Meteorological Organization. Technical Note No.114. W.M.O. - No. 274.TP.153. W.M.O., Geneva.

Freeman, M.H. (1961). Fronts Investigated by the Meteorological Research Flights. Meteorological Magazine 90, 189-203.

Garnett, A. (1971). Weather, Inversions and Air Pollution. Clean Air 1 (3), 16-21.

Garnett, A. (1976). Interrelationships in Air Pollution Studies. Paper presented at the Association of British Climatologists meeting, Institute of British Geographers Conference, Coventry, Jan. 6th-10th.

Garnett, A. and Bach, W. (1965). An Estimation of the Ratio of Artificial Heat Generation to Natural Radiation Heat in Sheffield. U.S. Monthly Weather Review 93, 383-385.

Garnett, A. and Read, P. (1972). Natural Gas as a Factor in Air Pollution Control. Comm. 868 Inst. Gas Engineers, 1-23.

Geiger, R. (1965). The Climate Near the Ground. Harvard University Press, Cambridge, Massachusetts.

George, (1958). The Geology and Geomorphology of the Glasgow District. In: Miller, R. and Tivy, J., The Glasgow Region, 17-62, Constable, Edinburgh.

Gilbert, O.L. (1968). Bryophytes as Indicators of Air Pollution in the Tyne Valley. New Phytol. 67, 15-30.

Gilbert, O.L. (1969). The Effects of SO_2 on Lichens and Bryophytes around Newcastle-upon-Tyne. In : Air Pollution, Proceedings of the first European Congress on the Influence of Air Pollution on Plants and Animals, 223-235. Wageningen : Centre for Agricultural Publishing and Documentation, Wageningen.

Gilbert, O.L. (1971). The Effect of Airborne Fluorides on Lichens. Lichenologist 5, 26-32.

Gillieland, A. (1979). Personal Communication.

Graedel, T.E. (1977). Distant Source Sensing by Statistical treatment of Air Quality Data. Atmospheric Environment 11 (4), 313-320.

Greenfield, S.M. (1957). Rain Scavenging of Radioactive Particulate Matter from the Atmosphere. Journal of Meteorology 14, 115-125.

Gregory, S. (1963). Statistical Methods and the Geographer. Longmans, London.

Guildberg, P. et al. (1977). Air Quality Impact of the Energy Shortage. Journal of Applied Meteorology 16, 3-10.

Hadley, G. (1735). Concerning the Cause of the General Tradewinds. Philosophical Transactions, London 29, 58-62.

Halstead, C.A. (1958). The Climate of the Glasgow Region. In : Miller, R. and Tivy, J., The Glasgow Region, 62-73, Constable, Edinburgh.

Halstead, C.A. (1973). Air pollution and relief in the Glasgow area. Geoforum, 14, 67-72.

Halstead, C.A. (1976). Plume Dispersal and Ground Level Concentrations - Some Outstanding Problems. University of Edinburgh 2nd Chimney Design Symposium 1, 9-13.

Hanibal, J. (1977). Personal Communication (Czechoslovakian Technical Air Pollution Inspectorate).

Hardy, R.N. (1973). Statistics of Inversions at Cardington in Bedfordshire. Meteorological Office Investigations Division Memorandum No. 108.

Hartley, M. (1977). Glasgow as an Urban Heat Island. Scottish Geographical Magazine 93, 80-90.

Hawksworth, D.L. and Rose, F. (1970). Qualitative Scale for Estimating Sulphur Dioxide Air Pollution in England and Wales Using Epiphytic Lichens. Nature 227, 145-148.

H.M.S.O. (1979). Digest of United Kingdom Energy Statistics 1979. Department of Energy, Her Majesty's Stationery Office, London.

Hoffman, C.H. and Linduska, J.P. (1949). Some Considerations of the Biological Effects of D.D.T. Scientific Monthly 69, 104-114.

Holt-Jensen, A. (1973). Acid Rains in Scandinavia. Ecologist 3(10), 378-382.

Holzworth, G.C. (1962). A Study of Air Pollution Potential for the Western United States. Journal of Applied Meteorology 1, 366-382.

Holzworth, G.C. (1972). Vertical Temperature Structure during the 1966 Thanksgiving Week Air Pollution Episode in New York City. U.S. Monthly Weather Review 100, 445-450.

Hood, N. and Young S. (1977). The Long-Term Impact of Multinational Enterprise on Industrial Geography : The Scottish Case. Scottish Geographical Magazine 93(3), 159-168.

Hosler, C.R. (1961). Low Level Inversion Frequency in the Contiguous United States. U.S. Monthly Weather Review 89, 319-339.

Jayaweera, K.O. (1973). Note. Journal of Applied Meteorology 12, 887.

Kazanski, A.B. and Monin, A.S. (1960). A Turbulent Regime above the Surface Atmosphere. Izvestiya - Academy of Sciences - Atmospheric and Oceanic Physics, Geof. Ser. 1, 110.

Keddie, A.W.C., Bower, J.S., Maughan, R.A., Roberts, G.H., and Williams, F.P. (1978). The Measurement, Assessment and Prediction of Air Pollution in the Forth Valley of Scotland - Final Report. Report LR 279(AP), Warren Spring Laboratory, Stevenage.

Keddie, A.W.C. and Williams, F.P. (1974). West Central Scotland Plan. Supplementary Report 5C, The Distribution of Air Pollution in West Central Scotland. West Central Scotland Plan, Glasgow.

Kelly, P.M. and Wright, P.B. (1978). The European Drought of 1975-76 and its Climatic Context. Progress in Physical Geography 2, 237-264.

Kumar, A. and Djurfors, S.G. (1977). A Model to Predict Violation of Clean Air Regulations. Paper presented at 4th Joint Conference on Sensing of Environmental Pollutants, New-Orleans, Nov. 6th-11th.

Lamb, H.H. (1972). British Isles Weather Types and a Register of the Daily Sequence of Circulation Patterns, 1861-1971. Met. Office Geophysical Memoirs No.116, H.M.S.O., London.

Landsberg, H.E. (1970). Man-Made Climatic Changes. Science 170, 1267-1274.

Lawrence, E.N. (1954). Nocturnal Winds. Professional Notes Meteorological Office 7, No.111. H.M.S.O., London.

Lawrence, E.N. (1962). Atmospheric Pollution in Hilly Terrain. International Journal of Air and Water Pollution 6, 5-26.

Lawrence, E.N. (1969). High Values of Atmospheric Pollution in Summer at Kew and the Associated Weather. Atmospheric Environment 3, 123-134.

Lawrence, E.N. (1967). Atmospheric Pollution During Spells of Low-Level Air Temperature Inversion. Atmospheric Environment 1, 561-576.

Ledbetter, J.O. (1972). Air Pollution. M. Dekker, New York.

Legrand, M. (1974). Statistical Studies of Urban Air Pollution - Sulfur Dioxide and Smoke. In : Prat, J., Statistical and Mathematical Aspects of Pollution Problems, 25-37, Marcel Dekker Inc., New York.

Leighton, P.A. (1971). Geographical Aspects of Air Pollution. In : Detwyler, T.R. (Ed.), Man's Impact on Environment, 113-131. McGraw-Hill Book Company, New York.

Leone, I.A., Brennan, E. and Daines, R. (1966). The Role of Wind Parameters in Determining SO_2 Concentrations in Carlstadt, New Jersey. International Journal of Air and Water Pollution 10(2), 113-124.

Logan W.P. (1953). Mortality in the London Fog Incident, 1952. The Lancet, 264, 336-338.

Lucas, D.H., Moore D.J., and Spurr, G. (1963). The Rise of Hot Plumes from Chimneys. Air and Water Pollution. International Journal 7, 473-500.

Lucas, D.H., James, K.W. and Davies, I. (1967). Paper I : The Measurement of Plume Rise and Dispersion at Tilbury Power Station. Atmospheric Environment 1, 353-365.

Lucas, D.H. (1971). Discussion. Atmospheric Environment 6, 781. Relates to: Leone, I.A. and Brennan, E. (1972). Surlfur Nutrition As it Contributes to the Susceptibility of Tobacco and Tomato to SO_2. Atmospheric Environment 6, 259-266.

Lucas, D.H. (1975). The Effect of Emission Height in Very Large Areas of Emission. Atmospheric Environment 9, 607-622.

Lynn, D.A. (1976). Air Pollution : Threat and Response. Addison-Wesley, Reading, Massachusetts.

Lyons, W.A. and Cole, H.S. (1976). Photochemical Oxidant Transport : Mesoscale Lake Breeze and Synoptic Scale Aspects. Journal of Applied Meteorology 15(7), 733-743.

Markee, E.H. (1961). Effects of Vertical Temperature Difference on Soiling Index. Journal of the Air Pollution Control Association 11(3).

McCarthy, R.L., Bower, F.A. and Jesson, J.P. (1977). The Fluorocarbon - Ozone Theory - I. Production and Release - World Production and Release of CCl_3F and CCl_2F (Fluorocarbons 11 and 12) Through 1975. Atmospheric Environment 11, 491-497.

McIntyre, R.J. and Thornton, J.R. (1978). On the Environmental Efficiency of Economic Systems. Soviet Studies 30, 173-192.

McKellar, H.A. (1969). The Success of Clean Air. Paper presented to Annual Conference of Scottish Division, National Society for Clean Air, Largs. Data post 1969 - Personal Communication.

McMahon, T.A. et al (1976). A Long Distance Air Pollution Transportation Model Incorporating Washout and Dry Deposition Components. Atmospheric Environment 10, 751-762.

Manley, G. (1952). Climate and the British Scene. Collins, London.

Marsh, K.J. and Foster, M.D. (1967). An Experimental Study of the Dispersion of the Emissions from Chimneys in Reading. Atmospheric Environment 1, 517-550.

Martin, A. and Barber, F. (1971). Control of Daily Sulphur Dioxide Instruments to Minimise Possible Errors. Atmospheric Environment 5, 423-428.

Meade, P.J. (1954). Smogs in Britain and the Associated Weather. International Journal of Air Pollution 2, 87-91.

Meetham, A.R. (1955). Know Your Fog. Weather 10, 103-105.

Meetham, A.R. (1964). Atmospheric Pollution : its Origins and Prevention. Pergamon Press, Oxford.

Mellanby, K. (1967). Pesticides and Pollution. Collins, London.

Meteorological Office Investigations Division (1963). Frequencies of Various Stabilities in the Surface Layer. Bannon, J.K., Dods, J. and Meade, P.J. Investigations Division Memoranda 88, Meteorological Office, Bracknell.

Mieber, H., Carter, W., Lloyd, A. and Pitts, J. (1976). The Effect of Latitude on the Potential for Photochemical Smog. Atmospheric Environment 10, 731-734.

Miller, R. (1958). The Geography of the Glasgow Region. In : Miller, R. and Tivy, J., The Glasgow Region, 1-17, Constable, Edinburgh.

Ministry of Housing and Local Government (1963). Clean Air Act, 1956 : Memorandum on Chimney Heights. H.M.S.O., London.

Ministry of Housing and Local Government (1967). Chimney Heights Memorandum. H.M.S.O., London.

Monteith, J.L. (1957). Dew. Quarterly Journal of the Royal Meteorological Society 83, 322-341.

Moore, D.J. (1967). Paper IV : SO_2 Concentration Measurements Near Tilbury Power Station. Atmospheric Environment 1, 389-410.

National Society for Clean Air (1971). Sulphur Dioxide. National Society for Clean Air, Brighton.

Nicholson, J., and Keddie, A.W.C. (1972). Scotland and Northern Ireland - National Survey, of Air Pollution 1961-71, H.M.S.O., London. (Also listed under Warren Spring Laboratory (1972)).

Nonhebel, G. (1960). Recommendations on Heights for New Industrial Chimneys. Journal of the Institute of Fuel 33, 479.

Nonhebel, G. (1969). Precognition. (Report Submitted to Inverkip Public Inquiry). Romsey, Hampshire.

Norcliffe, G.B. (1977). Inferential Statistics for Geographers. Hutchinson, London.

Nordoe, J. (1974). Quantitative Estimates of Long Range Sulphur Pollutants in Europe. Annalen de Meteorologie 9, 71-77.

Nyberg, A. (1970). On Transport of Sulphur Over the North Atlantic. Swedish Meteorological and Hydrological Institute. Rapporter Meteorologi och Klimatologi 6.

O'Hare, G. (1974). Air Pollution and Lichens in the Western Central Lowlands of Scotland. Ph.D. thesis, University of Glasgow.

Ollswang, G. (1972). Air Pollution in West Central Scotland. Built Environment 1972, 331-334.

Open University (1975). Environmental Control and Public Health. Air Pollution Units 13 and 14. Open University Press, Milton Keynes.

Organisation for Economic Co-operation and Development (1964). Methods of Measuring Air Pollution. O.E.C.D., Paris.

Pack, H. (1964). Meteorology of Air Pollution. Science 146, 1119-1128.

Parry, M. (1970). Sources of Reading's Air Pollution. World Meteorological Organization Technical Note No. 108, W.M.O. No. 254,TP.141., W.M.O., Geneva.

Pasquill, F. (1961). The Estimation of the Dispersion of Windborne Material. Meteorological Magazine 90, 33-50.

Pasquill, F. (1962). Atmospheric Diffusion Van Nostrand, Amsterdam.

Pasquill, F. (1971). Atmospheric Dispersion of Pollution. Quarterly Journal of the Royal Meteorological Society 97, 369-395.

Peakall, D.B. (1976). D.D.T. in Rainwater in New York Following Application in the Pacific North West. Atmospheric Environment 10, 889-900.

Pilie, R.J., Mack, E.J., Kocmond, W.C., Rogers, C.W. and Eadie, W.J. (1975). The Life Cycle of Valley Fog. Part I : Micrometeorological Characteristics. Journal of Applied Meteorology 14, 347-363.

Plant, J.A. (1967). The Climate of Glasgow. Climatological Memorandum 60, Meteorological Climatological Services (Met. 03), Bracknell.

Ragland, K.W. (1976). Worst Case Ambient Air Concentrations from Point Sources Using the Gaussian Plume Model. Atmospheric Environment 10, 371-374.

Rasool, S.I. and Schneider, S.H. (1971). Atmospheric Carbon Dioxide and Aerosols : Effects of Large Increases on Global Climate. Science 173, 138-141.

Rees, J.A. (1977). The Economics of Environmental Management. Geography 62, 311-324.

Reiher, M.V. (1936). Nächtlicher Kaltluftfluss an Hindernissen. Bioklimatische Beiblätter Braunschweig 3, 152-163.

Roach, W.T. (1976). On Some Quasi-Periodic Oscillations Observed During a Field Investigation of Radiation Fog. Quarterly Journal of the Royal Meteorological Society 102, 355-359.

Roach, W.T., Brown, R., Caughey, S.J., Garland, J.A. and Readings, C.J. (1976). The Physics of Radiation Fog : I - a field study. Quarterly Journal of the Royal Meteorological Society 102, 313-333.

Rodhe, B. (1962). The Effect of Turbulence on Fog Formation. Tellus 14, 49-86.

Rossby, C. (1940). Planetary Flow Patterns in the Atmosphere. Quarterly Journal of the Royal Meteorological Society 66, 68-87.

Saarinen, T.F. (1966). Perception of Drought Hazard on the Great Plains. University of Chicago, Department of Geography, Research Paper No. 106.

Saunders, W.E. (1960). The Clearance of Water Fog Following the Arrival of a Cloud Sheet During the Night. Meteorological Magazine 89, 8-10.

Scheffer, T.C. and Hedgecock, G.C. (1955). Injury to Northwestern Forest Trees by Sulphur Dioxide from Smelters. U.S. Dept. of Agriculture Technical Bulletin No. 1117, 49.

Schmidt, F.H. and Velds, C.A. (1969). On the Relations between Changing Meteorological Circumstances and the Decrease of Sulphur Dioxide Concentrations Around Rotterdam. Atmospheric Environment 3, 455-460.

Schwegler, H. (1967). Meteorological Location of Munich with regard to Air Pollution. Meteorologishe Rundschau 20, 166-168.

Scorer, R.S. (1968). Air Pollution. Pergamon Press, London.

Scottish Council (Development and Industry). (1970). Oceanspan I : a Maritime Based Strategy for a European Scotland 1970-2000. Scottish Council, Edinburgh.

Scottish Council (Development and Industry). (1971). Oceanspan II : a Study of Port and Industrial Development in Western Europe, Scottish Council, Edinburgh.

Scriven, R.A. (1967). Properties of the Maximum Ground Level Concentration from an Elevated Source. Atmospheric Environment 1, 411-419.

Selikoff, I.J., Hammond, E.C., and Churg, J. (1969). Mortality Experiences of Asbestos Insulation Workers. In : Shapiro, H.A. (Ed.), Pneumoconiosis, Proceedings of the International Conference, Johannesburg, 1969, 183, Oxford University Press, Cape Town.

Sellers, W.D. (1969). A Global Climatic Model Based on the Energy Balance of the Earth-Atmosphere System. Journal of Applied Meteorology 8, 392-400.

Shellard, H.C. and Hay, R.F. (1961). Incidence of and Some Rules for Forecasting Temperature Inversions over the North East Atlantic. Meteorological Office Scientific Paper No. 10.

Shevchuk, I.A., Vvedenskaya, L.I. and Volodkevich, T.G. (1969). Frequency of Meteorological Conditions Promoting Atmospheric Pollution in the Layer of the Atmosphere Next to the Earth in the Town of Novosibirsk. Trudy-Novosibirskii Regionalnyi Gidrometeoroligicheskii Tsentr 2, 106-109.

Simon, H.A. (1956). Rational Choice and the Structure of the Environment. Psychological Review 63, 129-138.

Slade, D.H. (1968). Meteorology and Atomic Energy. Atomic-Energy Commission, Washington.

Smagorinsky, J. (1963). General Circulation Experiments with the primitive equations, I : The Basic Experiment. U.S. Monthly Weather Review 91(3), 99-104.

Smith, F.B. (1972). A Scheme for Estimating the Vertical Dispersion of a Plume from a Source Near Ground Level. Proceedings of the Third Meeting of the Panel on Air Pollution Modelling, N.A.T.O./C.C.M.S., Paris.

Smith, F.B. and Jeffrey, G.H. (1971). The prediction of high concentrations of sulphur dioxide in the London air. Meteorological Office T.D.N. 19, London.

Smith, K. (1975). Principles of Applied Climatology. McGraw-Hill, London.

Smith, M.E. (1973). Recommended Guide for the Prediction of the Dispersion of Airborne Effluents. American Society of Mechanical Engineers, 2nd Edition, New York.

Solow, R.M. (1971). The Economist's Approach to Pollution and Its Control. Science 173, 498-503.

Sonkin, L. and Khrapachenko, V.A. (1973). Influence of Meteorological Conditions on the Content of Contaminants in City Air During Summer. In : Atmosfernaya Diffuziyai Zagrryaznenie Vozdukha, Vypusk 293, Gidrometeoizdat, Leningrad. Translated : Beryland, M.E. (ed.) Air Pollution and Atmospheric Diffusion, Jerusalem.

South of Scotland Electricity Board (1973). Annual Report and Accounts. S.S.E.B., Glasgow.

South of Scotland Electricity Board (1977). Annual Report and Accounts. S.S.E.B., Glasgow.

Sphere (1974). Renfrewshire Infra-Red Aerial Survey and Analysis of Pollution Induced Vegetation Damage. Sphere, London.

Stewart, H., Sullivan, E. and Williams, M. (1976). Ozone Levels in Central London. Nature 263, 582-584.

Sutton, O.G. (1947). Theoretical Distribution of Air-borne Pollution from Factory Chimneys. Quarterly Journal of the Royal Meteorological Society 73, 426.

Swedish Royal Ministry for Foreign Affairs and the Royal Ministry of Agriculture (1971). Air Pollution Across National Boundaries. The Impact on the Environment of Sulfur in Air and Precipitation, Sweden's Case Study for the United Nations Conference on the Human Environment. Swedish Preparatory Committee for the United Nations Conference on the Human Environment, Stockholm.

Sweeney, J.C. (1979). Inversion Persistence at Long Kesh Northern Ireland. Weather 34(2), 50-59.

Taylor, G.I. (1917). The Formation of Fog and Mists. Quarterly Journal of the Royal Meteorological Society 43, 241-268.

Tukey, J.W. (1970). Exploratory Data Analysis Vol. I., Addison-Wesley, Reading, Massachusetts.

Turner, D. Bruce (1964). A Diffusion Model for an Urban Area. Journal of Applied Meteorology 3, 83-91.

Turner, D.B. (1970). Workbook of Atmospheric Dispersion Estimates. U.S. Environmental Protection Agency, AP-26.

Tyson, P.D. (1968). Nocturnal Local Winds in a Drakensberg Valley. The South African Geographical Journal 50, 15-33.

Tyson, P.D. (1969). Air Pollution Fumigation Conditions Associated with the Dissipation of the Mountain Wind and the Onset of the Valley Wind over Pietermaritzburg. The South African Geographical Journal 51, 99-106.

U.S. Department of Health, Education and Welfare (1969, 1970, 1971). Air Quality Criteria, Summary and Conclusions. U.S.D.H.E.W., Washington.

United States Environmental Protection Agency (1973). Report of Hearings Panel. National Public Hearings on Power Plant Compliance with Sulphur Oxide Air Pollution Regulations, 18th October - 2nd November 1973. E.P.A., Washington.

Van Dop, H. and Kruizinga, S. (1976). The Decrease of Sulphur Dioxide Concentrations Near Rotterdam and their Relation to some Meteorological Parameters During Thirteen Consecutive Winters (1961-1974). Atmospheric Environment 10, 1-4.

Vdovin, B.J. (1974). Stratification Features of the Bottom One Kilometre Layer of the Atmosphere over Leningrad obtained by Helicopter Observations. In : Atmosfernaya Diffuziyai Zagrryaznenie Vozdukha, Vypusk 293 Gidrometeoizdat, Leningrad. Translated : Beryland, M.E. (Ed.). Air Pollution and Atmospheric Diffusion, Jerusalem.

Voloshin, V.G. (1973). Duration of Inversions and Light Wind Periods in the Boundary Layer of the Atmosphere. In : Atmosfernaya Diffuziyai Zagrryaznenie Vozdukha, Vypusk 293, Gidrometeoizdat, Leningrad. Translated : Beryland, M.E. (ed.). Air Pollution and Atmospheric Diffusion, Jerusalem, 1974.

Wallace, N.G. (1979). Personal Communication.

Warren Spring Laboratory (1966). National Survey of Smoke and Sulphur Dioxide. Instruction Manual. Warren Spring Laboratory, Stevenage.

Warren Spring Laboratory (1972). National Survey of Air Pollution 1961-71. H.M.S.O., London.

Warren Spring Laboratory (1974). Forth Valley Survey - Summary Report on First Year's Data. Scottish Development Department, Edinburgh.

Warren Spring Laboratory (1976). Forth Valley Survey - Summary Report on Second Year's Data. Scottish Development Department, Edinburgh.

Warren Spring Laboratory (1979). Winter Mean Concentration Maps of Smoke and SO_2 1975-76. Warren Spring Laboratory, Stevenage.

Weddle, A.E. (1969). Report on Possible Industrial Developments in the Clyde Estuary. Clyde Estuary Development Group, Glasgow.

Williams, W.J. et al (1977). Air Pollution Damage to the Forests of the Sierra Nevada Mountains of California. Environmental Conservation 3, 227-230.

Wyckoff, R.J. (1973). A Comparison of the Low Level Radiosonde and the Acoustic Echo Sounder for Monitoring Atmospheric Stability. Journal of Applied Meteorology 12, 1196-1204.

ADDENDUM

References for Tables

American Chemical Society, (1969). Cleaning Our Environment. Report on the American Chemical Society, Washington.

Derwent, R.G. and Stewart, H.N.M. (1973). Pollution from Oxides of Nitrogen in the United Kingdom. Atmospheric Environment 7(4), 385-402.

Lynn, D.A. and McMullen, T.B. (1966). Air Pollution in Six Major U.S. Cities as Measured by the Continuous Air Monitoring Program. Journal of the Air Pollution Control Association 16(4), 186-190.

McManus, T. and Reilly, M. (1977). Air Pollution Standards. Technology Ireland 9(3), p. 23-29.

Vandegrift, A. et al (1971). Particulate Air Pollution in the United States. Journal of the Air Pollution Control Association 21.

GLASGOW
UNIVERSITY
LIBRARY