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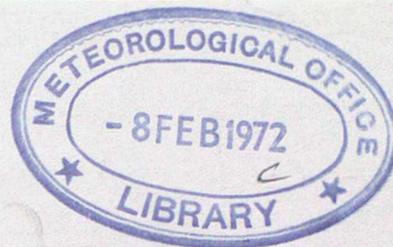
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The Prediction of High Concentrations of Sulphur Dioxide in London Air

by F. B. Smith and G. H. Jeffrey

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1. Introduction

High concentrations of sulphur dioxide in the atmosphere can cause considerable upset to people with bronchial troubles, particularly if the concentrations are maintained over a period of days. One of the most unpleasant results of the famous London smog of 1952 was the very high mortality rate caused by bronchitis and other related ailments during the subsequent week; overall it was estimated the smog caused between 3,500 and 4,000 deaths (see "Air Pollution and Health", 1970). Hospital places were also in tremendous demand by less seriously affected sufferers.

Quoting from the same source, absenteeism tends to rise rapidly among London factory and office workers whenever the daily average SO_2 concentration exceeds $250 \mu g/m^3$ (not a particularly high value in London) and, in Salford, absenteeism is twice that of the daily average amongst all workers when the concentration reaches $1000 \mu g/m^3$ (a rather more exceptional level).

Even the most cursory investigation of weather conditions on days of high SO_2 concentration reveals that cold and relatively calm days in winter are frequently the most dangerous. The Meteorological Office in London was therefore asked over eight years ago to provide a forecasting service of those meteorological conditions which were likely to lead to significantly high concentrations and a subsequent demand on hospital beds. The criterion chosen was for a concentration of at least $1000mg/100m^3$ (ie $10,000 \mu g/m^3$). As a daily mean value (or, one suspects, even an hourly mean value) this is quite beyond the range of present day values, and even allowing for the effects of the Clean Air Act in somewhat reducing typical SO_2 concentrations, it seems unlikely ever to have occurred, except possibly very close to a strong source and over very short periods of time. During the 1952 smog the maximum average SO_2 concentration over 10 sampling stations was approximately $2000 \mu g/m^3$, and this in itself is about double the greatest SO_2 concentration experienced from 1968 to 1970 inclusive when averaged over four stations, with a typical mean somewhat above the Inner London average. In the original scheme developed to meet this demand, the meteorological conditions which were expected to lead to critical concentrations were as follows:

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(a) An expectation of less than 2/8ths of cloud, or of sky obscured by fog at 18Z, 00Z and 06Z,

(b) an expectation of a mean of surface wind speeds at 18Z, 00Z and 06Z of less than 3 knots, the actual speed at each of these hours being less than 5 knots,

(c) an instability index $S = (2T_x - 3T_n - 12) \geqslant 0$, where T_x is the highest temperature expected at midnight at Crawley at any level up to and including 900 mb (but excluding the surface) and T_n is the forecast minimum temperature at Heathrow (temperatures are in $^{\circ}C$). If (a), (b) and (c) are satisfied a forecast of high pollution is issued, but if in (c) we only have $-3 \leqslant S < 0$ then a more cautious forecast is made.

The London Weather Centre, which is responsible for making the forecasts, has felt that a re-appraisal of the scheme is called for; partially because the scheme did not appear to be highly successful and partially because the Clean Air Act has reduced the overall SO_2 low-level emission rates.

With growing concern all over the world over the state of urban environments, many alternative forecasting schemes have been developed, and several of these are reported in the literature. These generally fall into one of three groups.

(i) Numerical models. Whenever source distributions are reasonably well known both in time and space, the equations of diffusion may be used to calculate spatial distributions of pollution, provided the wind and turbulence characteristics can be adequately prescribed and predicted. Such calculations require considerable computer facilities, and can only be meaningful on a scale large compared with the typical distance separating those sources which are not individually represented but are merged into area sources.

(ii) Physical models. Detailed models of urban areas have been created in large wind tunnels and the dispersion of pollution emitted in life-like manner from one or more sources studied. The advantage of this system is that the proposed addition of a new major source into an urban environment can be studied fairly realistically, even when the local topography is quite complex. Perhaps their chief disadvantage lies in the difficulty in simulating the wide range of meteorological parameters that affect dispersion: low-level inversions, fogs, solar radiation, wind direction and so on.   Their use is therefore more in the urban planning field than in routine day-by-day predictive work.

(iii) Empirical models. The scheme outlined above is one such model. The physics of the whole dispersion process only enters in at a comparatively low level but the scheme does have the advantage that it is based on real

data taken in real situations. Considering the very considerable complexity of the problem in an urban environment, the empirical approach may be the only really practical one on a day-by-day basis whenever a sufficient body of data is available for post-facto analysis (say at least two years of measurements of SO_2 and the weather). Since such measurements are readily available in London, our revised scheme described in later sections is also of this type.

2.   The measurements of sulphur dioxide

Inner (central) London as defined by Weatherley and Gooriah (1970) comprises an area 30 km by 20 km encompassing Hendon in the NW, Dagenham in the NE, Sidcup in the SE and Wimbledon in the SW. Within this area the National Survey sampling network has nearly one hundred sites in operation (the exact number varies between 90 and 100 from year to year). The area contains industry, scattered mainly around the River Thames and along the Lea Valley, as well as housing and commerce regions with substantial fuel consumption. Parks and comparatively low density housing areas (less than 5000 people per square km) are also present, so that the source distribution and the actual concentration distribution are far from simple (see Figs 1, 2, 3, 10, 11). Inspection of the Figures shows that the correspondence between source and concentration, as represented, is not particularly strong on a scale of one or two kilometres, but is much better on a scale of five to ten kilometres. This perhaps indicates that individual sites may often be significantly influenced by one or two fairly dominant local sources, and only when the concentrations are averaged over, say, four or more sites do they begin to have an obvious meaning in relation to broad area source-values. Figure 1 shows population density and the main industrial areas and comes from Weatherley and Gooriah. Figure 2 shows values of the mean SO_2 winter-values derived from the ten yearly values for each Inner London station in which the smoothed overall trend over the period is linearly extrapolated one year to 1969-70. The mean for all the stations is $231\mu g/m^3$; however the area-density of stations is not uniform and if isopleths of mean concentration are drawn (ignoring all the possible pitfalls in doing this) the mean concentration determined on an area basis is approximately $213\mu g/m^3$. The overall pattern appears to change little from year to year (c.f. Figs 3 and 10) but on a shorter timescale significant changes from day to day probably occur due to changes in source strength and wind direction. If Figure 2 is representative, concentrations within Inner London vary from at least half to twice the area mean on any occasion. The highest values are in Westminster where since industrial undertakings are few, road traffic and office-block central heating systems may be the most significant polluters of the urban

environment.

Figure 4 shows two concentration-direction roses, one for Kensington (site 4), the other for Deptford (site 3).   The radius in any direction represents the smoothed mean concentration, relative to the mean for all conditions, when the wind is coming from that direction.   An almost 3 to 1 variation in mean concentration with wind direction is implied at both stations, and this appears to be fairly typical.

3.   Meteorological parameters

The analysis of SO_2 concentrations at Kelvedon Hatch which preceeded the present London analysis, (see the Appendix), revealed that day to day values depended significantly upon the following parameters:

(i)   wind direction: effective source strengths vary with direction as exampled in the last section.

(ii)   temperature: source strength in the UK tends to be greater at lower temperatures, and hence generally in winter than in summer.   Temperature is also correlated with other meteorological factors that influence the dispersion of the SO_2.

(iii) wind speed: wind speed affects the stability of the atmosphere and hence the vertical dispersion of SO_2.   For a specified emission rate of SO_2 the concentration immediately downwind of the source tends to be inversely proportional to the wind speed.   It is probable that when ventilation by the exterior wind significantly affects offices and homes, the production of SO_2 increases, following the increase in compensatory heating.   Some of these trends are clearly in opposing directions and, at Kelvedon Hatch at least, were almost self cancelling.   In London itself wind speed appears to remain important, particularly at light winds when accumulation of SO_2 within the same mass of air leads to the highest concentrations recorded.

(iv) mixing depth or stability: dispersion through the vertical of SO_2 depends on the intensity of vertical turbulence.   Quite frequently a layer near the ground which is well mixed by turbulence is "capped" by a thermal inversion which inhibits further spreading of the pollutant to greater heights.   The pollutant is thus trapped and concentrations tend to a value inversely proportional to the height of the inversion.   At places well away from the major source of pollution (e.g. Kelvedon Hatch, some 30 km out from the centre of London), the mixing depth is one of the most important parameters since the approach to uniform mixing below the inversion has time to take place.   Within London itself where the typical distance between source and receptor is much less, the mixing depth ceases

to have this importance, except when it is very small.

The determination of the mixing depth and how a mean reciprocal mixing depth (MRMD) may then be found, to which the day's average concentration may be compared, is described in the Appendix.

The post-facto meteorological data have been obtained from Kew records with the exception of the Balthum ascent data from Cardington used in the determination of mixing depth.

After consideration and experiment it seemed that the most relevant parameters could be defined as follows:

(a) wind direction: Kew 10 metre wind directions, using the tabulated mean over the preceeding hour, averaged over twelve hours centred at 15Z during the day when the concentration sample is started. (National Survey one-day samples start in the morning at an assumed time between 09Z and 10Z and finish 24 hours later). If the wind direction varied by more than 60° during the period the direction is described as "Variable" and treated as a separate category. Further if there are at least 5 hours of calm (wind speed effectively zero) during the period the direction is described as "Calm" and treated as a further separate category.

(b) temperature: the Kew minimum hourly temperature during the period 10Z to 24Z on the day when the sample is started. The reasons for this choice are:

  (i) temperatures after midnight are not expected to be very relevant since emission rates are then normally quite low.

  (ii) the minimum temperature is likely to be well correlated with the overall coldness of the late afternoon and evening, and hence the domestic heating output.

(c) wind speed: two wind speed parameters are extracted: the first is the number of hours when the hourly-mean wind speed (Kew 10-metre value) is 2 knots or less. For simplicity we call this the number of hours of calm. The second parameter is the mean wind speed for the full day on which the sample is started. Logically a mean speed over the precise period of the sample should have been taken but the sidereal day mean was already tabulated and thus saved quite an amount of laborious computation at the expense of some accuracy.

(d) the mean reciprocal mixing depth (MRMD): see the Appendix. The London analysis indicates that only in situations with high values of this parameter ($\geqslant 8$), corresponding to low mixing depths, did the MRMD become

significant as a predictor.   During the winter months either of the following
criteria almost always are necessary and sufficient for an MRMD ⩾8:

(i)   surface inversion sets in before 18Z, and during the day cloud
height at or below 500m, or

(ii)   surface inversion sets in between 18 and 21Z, and during the day
inversion or cloud height at or below 300m.

The rules for surface inversions during the winter are:

(i)   At 18Z: assume a surface inversion unless wind speed > 8kts or
cloud amount > $\frac{5}{8}$ths.

(ii)   At 21Z and 24Z: assume a surface inversion unless wind speed
>8kts or cloud amount $^8/_8$ths.

4.   The SO_2-concentration data

Ideally all sampling stations in the Inner London area should have been
used in the analysis.   However certain factors weighed against this: for
various reasons not all stations maintain a regular day-by-day sampling routine.
Further it was decided in this exploratory analysis to limit the amount of data to
that which could be handled and analysed fairly easily using a desk electronic
computer, the Olivetti Programma 101.

Consequently four stations with a good record of completeness were selected
and permission to use their data was kindly granted by the Councils concerned.
These stations are:

> Kensington, Site 4
> City of London, Site 17
> Hackney, Site 2
> Deptford, Site 3.

Mean concentrations for a particular day were evaluated whenever either three
or four of the stations gave readings.   In the former case the mean was given the
appropriate weighting to balance the omission of one of the readings:

$$\begin{pmatrix} \text{Expected mean concentration} \\ \text{when } C_4 \text{ is missing} \end{pmatrix} = \frac{1}{4}(C_1 + C_2 + C_3)\left(\frac{m_1 + m_2 + m_3 + m_4}{m_1 + m_2 + m_3}\right)$$

where C_1, C_2 and C_3 are the day's readings at the 3 given sites; m_1, m_2, m_3 and m_4
are the long-term mean concentrations.   For the two winter periods that are studied
in detail in this analysis (the winter of 1968-69 and that of 1969-70) they take
the following values:

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m (Kensington) = 364 μg/m^3

m (City of London) = 415

m (Hackney) = 376

m (Deptford) = 253

Winter covers the months from October to March inclusive.

No readings were taken on Saturdays or Sundays, and Monday's readings represent combined values for the three weekend days. Three days out of seven are therefore not available for the present analysis. Public holidays are also sometimes missed. In all, 194 days had three or four readings at the sites and this is in fact a very high proportion of the total possible number of days.

The mean concentrations are **higher by some 11% than** the winter averages for the two years given in the annual Warren Spring Laboratory Reports "Investigation of Air Pollution", largely it seems because the omitted weekend concentrations are on average lower than the midweek concentrations. The two-year winter averages, on the other hand, are **satisfactorily close to the five-year winter** averages.

Concentrations at the four sites are not of course perfectly correlated on a day-to-day basis, partially because changes of wind direction change the source distributions which affect each sampler, and partially because of normal variations in source output from each and every source. The correlation coefficients between the concentrations at the sites vary from about 0.44 to 0.68. Now if we may assume that $C/\overline{C}$ (where $\overline{C}$ is the time-mean concentration at one site, and C is a one-day concentration at the same site) has a statistical day-by-day distribution which is virtually the same irrespective of site, then

$$\sigma^2 = (1-r) \ s^2$$

where σ = the standard deviation of the "random" component of the concentration
C which is uncorrelated from site to site

r = the site to site correlation coefficient

s = the standard deviation of the concentration values at any site.

Typically then, $r \approx 0.56$ and $s \approx 180 \mu$g/m^3. Roughly, we deduce that $\sigma \approx 100 \mu$g/m^3. This implies that the concentration at any site on any day cannot be specified, even when the Inner London mean concentration is known, to within an error e which has a standard deviation $\sigma \approx 100 \mu$g/m^3.

Averaging the concentrations over four sites reduces this error by $4^{\frac{1}{2}}$, ie the standard error is now 50μg/m^3. Averaging over all the 94 sites would reduce the standard error further to about 10μg/m^3. The random error for the

four sites must be one of the reasons for the failures, albeit a relatively small number of failures, in the forecasting scheme described later.

Figure 5 shows the histogram of 290 mean winter concentrations for 5 years for all the Inner London stations, when means could be evaluated, taken from the Warren Spring Laboratory Annual Reports (loc. cit.). Figure 6 shows that when plotted on log-probability paper the histogram conforms quite closely to a log-normal distribution with a median of 235 $\mu g/m^3$. This best-fit distribution is shown on Figure 5. The mean (including weekends) of the four stations is 310 $\mu g/m^3$, and thus some 20% of Inner London may be expected to experience concentrations greater than the average of the four stations on a winter basis, and with less certainty on a daily basis. If the log-normal hypothesis is correct some 0.2% (i.e. 1.2 sq km) of the total area may experience twice the four-station average.

To separate more clearly the spatial and temporal distributions of concentration, Figures 7 and 8 show the cumulative frequency curves for the concentrations meaned over the five winters 1965-70 for all the Inner London sites for which values could be obtained, and for the daily concentration values, meaned over the four sites, for the two winter periods under survey, 1968-69 and 1969-70. Both curves show a close approximation to log-normal distributions.

To support the hypothesis that the log-normal distribution is a satisfactory fit, at least over the inner 90% of the distribution, the following test may be applied:

If C_m = the median concentration of the distribution
$\overline{C}$ = the mean concentration of the distribution
σ = the standard deviation of lnC
s = the standard deviation of C

then for a log-normal distribution:

$$\overline{C} = C_m \exp(\tfrac{1}{2}\sigma^2) \tag{1}$$

and $$s^2 = (\overline{C}^2 - C_m^2)\overline{C}^2/C_m^2 \tag{2}$$

C_m is calculated by forming the geometric mean of all the concentration values in the sample and is a theoretically better estimate of the parent population median concentration than is $\overline{C}$, the arithmetic mean, of the parent population mean concentration. Similarly σ is more reliable than s.

Applied to the 73 data values involved in Figure 7:

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FROM THE DATA	CALCULATED FROM EQNS (1) & (2)
$C_m = 227.1$ $\overline{C} = 238.6$	$\overline{C} = 238.0$
$\sigma = 0.313$ $s = 76.8$	$s = 74.6$

The median evaluated by its fundamental definition, namely by the value which equally divides the data points (50% having a higher concentration and 50% a lower) is $C_m = 231 \mu g/m^3$. However this is a less accurate method of estimating the parent population C_m from a sample on the assumption of a log-normal distribution.

The close agreement between the calculated and derived values of $\overline{C}$ and s strongly support the log-normal hypothesis. The advantage of this hypothesis is that it enables us to estimate the likely area in Inner London in which the concentration of SO_2 may exceed some defined critical level at any time. However the hypothesis must remain of doubtful validity "out on its tails", i.e. when the area becomes smaller than about 10 sq km, and too much reliance should not be placed on forecasts in these circumstances without a much more detailed investigation than is given here.

One final point concerning these statistics may be made. The geographical distributions of

(i)   the mean concentrations for the winters under analysis

(ii)   the number of days with concentrations exceeding $500 \mu g/m^3$ shown in Figures 9 and 10, are very similar. The following approximate correspondences apply:

Number of days with $\overline{C} \geqslant 500 \mu g/m^3$ over two winters	Mean concentration for the same two winters
0	$150 \mu g/m^3$
10	200
25	300
50	360
100	400

These relations should be roughly consistent with the log-normal time distributions of concentration.

5.   The variation of concentration with meteorological parameters

Section 3 described the meteorological parameters that appeared to be significant.

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Table 1 gives the variation of mean concentration, averaged over the four sites, with wind direction:

Wind Direction	Mean concentration	Wind Direction	Mean concentration
001 - 030	243 μ g/m^3	181 - 210	235
031 - 060	271	211 - 240	204
061 - 090	351	241 - 270	223
091 - 120	395	271 - 300	232
121 - 150	302	301 - 330	323
151 - 180	268	331 - 360	279
Variable	307	Calm	306

TABLE 1

Table 2 sets out in detail all the basic data, some of which has already been defined in Section 3. The column headed MRMD gives the mean reciprocal mixing depth described in the Appendix, and evaluated by that method. The final column represents the results of the objective post-facto forecasting scheme. The following key explains the nomenclature in this column:

Key to final column
of Table 2

A: forecast concentration exceeding 400 μ g/m^3, or a normalised concentration exceeding 1.5. The second alternative allows for concentrations below 400 which for that wind direction are nevertheless high. Normalised concentration is defined as the ratio of the actual concentration to the mean concentration for that particular wind direction.

B: forecast concentration exceeding 600 μ g/m^3.

=: correct forecast

X: incorrect forecast, either a predicted A or B not born out in practice, or no forecast of A or B when there should have been.

The forecast scheme was developed empirically by considering the concentration values and the appropriate meteorological parameters for the first winter 1968-69. When applied to the second winter 1969-70 the scheme proved to be equally successful without any further modification or elaboration of the rules. The rules may be stated quite simply:

The Forecasting Scheme

1. A concentration averaged over the usual 24 hour period at the four stations: Kensington 4, City of London 17, Hackney 2, Deptford 3, will exceed

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$400 \mu g/m^3$, (or, in the case of those wind directions which on average have low SO_2 concentrations, a normalised concentration exceeding 1.5) whenever at least one of the following conditions is fulfilled:

(i) the number of hours with mean wind speed less or equal to 2 knots greater or equal to 8 hours (see column 5: Table 2)

(ii) minimum temperature (col 7) $\leq 0^{\circ}C$, and at least one hour light winds (col 5)

(iii) the MRMD (col 8) ≥ 8 and minimum temperature (col 7) $\leq 6^{\circ}C$, and mean wind (col 6) ≤ 10 knots

(iv) concentration for previous 24 hours estimated greater than $600 \mu g/m^3$ and minimum temperature (col 7) $\leq 4^{\circ}C$ and mean wind (col 6) ≤ 10 kts.

2. The concentration defined in 1 above will exceed $600 \mu g/m^3$ whenever

(i) the minimum temperature (col 7) is less than $5^{\circ}C$

and at least one of the following conditions is fulfilled:

(ii) light winds (col 5) for 19 or more hours

(iii) concentration for previous 24 hours estimated to exceed $400 \mu g/m^3$ and minimum temperature (col 7) $< 0^{\circ}C$ and at least two hours with light winds (col 5)

(iv) concentration for previous 24 hours estimated to exceed $400 \mu g/m^3$ and light winds (col 5) for at least 10 hours.

The results displayed in Table 2 may be summarised in the following Tables:

(A) <u>Contingency Table for success in forecasting A</u>
(i.e. either $C \geq 400 \mu g/m^3$, or normalised $C \geq 1.5$)

	high concentration A	lower concentration not A	TOTAL
forecasting success =	56　　29%	107　　55%	163　　84%
forecasting failure x	14　　7%	16　　8%	30　　16%
TOTAL	70　　36%	123　　64%	193

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(B) Contingency Table for success in forecasting B
(i.e. $C \geqslant 600 \mu g/m^3$)

	very high concentration B	lower concentration not B	TOTAL
forecasting success =	11 6%	178 92%	184 98%
forecasting failure ×	3 (all 3 are A =) 1.5%	1 0.5%	4 2%
TOTAL	14 7%	179 93%	193

* Percentages in general have been rounded to the nearest whole number.

In both cases when a forecast of high pollution is made a success rate of about 80% is achieved.

Some important points must be made:

(i)   The threshold values 400 and $600 \mu g/m^3$ are not universal values.   They are only meaningful in so far as the source distribution and output remains basically unaltered.   Whilst it is virtually impossible over a short period of time to identify any such change, it is recommended that the two values be suitably modified if necessary once every five years in the light of the overall changes in mean winter concentration at the four sites over the preceeding five years.

(ii)   No attempt has been made in this analysis to relate the concentration values to the effect on people's health and the likely demands on the facilities at the two hospitals concerned.   This is largely a medical problem and lies outside our capabilities.

(iii) In the previous scheme a forecast had to be made before 1600Z of the chances of high pollution during the evening and night that followed.   We have moved to a different problem, partially because our basic concentration data are daily mean values (rather than hour by hour values) and also because we feel that the problem is not solely a night-time problem.   At night many people, and particularly bronchitic sufferers, are likely to be in the shelter of their own homes where they can to some extent regulate the condition of the air they breathe, whereas during the day they are more likely to be out and about, being affected by atmospheric concentrations of SO_2 which are not necessarily a great deal less than the evening concentration.   Our aim has therefore been to

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forecast the mean concentration for the whole 24-hour day.   The forecast of the meteorological conditions is therefore longer-range and to that extent more liable to error.

Ideally, then, a forecast should be made in the early morning, before 1000Z, of the meteorological conditions for the next 24 hours and hence the likely mean concentration.   Since many of the criteria in the forecasting scheme relate to evening conditions (and hence are not altogether different in intent from the previous scheme), some revision of the concentration forecast could be made as late as 1600Z whenever this seemed called for.

(iv) The results set out above refer to a post-facto application of the scheme using meteorological data as it actually occurred.   In day-by-day application of the scheme in the future these data will have to be forecast. This is bound to introduce significant errors which may be even greater than those implied in the Tables above.

Some of the parameters, such as the minimum temperature and the cloud amounts, are already estimated on a routine basis for other purposes.   The criterion of the number of hours when the mean wind falls below 2 knots is probably the hardest to estimate with any certainty, but clearly this is a very important parameter and one that some effort should be put into to forecast adequately.

6.   Conclusions

A scheme for forecasting the incidence of high levels of sulphur dioxide daily-mean concentrations has been derived for Inner London.   Post-facto forecasts of high levels have achieved 80% success for the two winters 1968-69 and 1969-70.   Application as a routine forecasting scheme is likely to have a somewhat lower success-rate due to errors in forecasting the relevant meteorological parameters over the subsequent 24-hour period.   The threshold concentration values of 400 and 600 $\mu g/m^3$ refer to the mean of four sites in Inner London, and should be revised periodically as overall pollution levels alter.   The mean and extremes of the concentration over the whole area may be deduced on the basis of the log-normal distribution hypothesis which appears to be valid.   Geographical distributions of concentration over the area have only been assessed at this stage over monthly, or longer, periods.   These distributions are reasonably stable, but from day-to-day with different wind directions the pattern is likely to change.   (See Figures 2, 3, 10 and 11).

The scheme can strictly only be applied from Monday to Friday.   Weekends and Public Holidays are likely to have smaller and different source-strength

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distributions which may alter the threshold values in a way we have so far not assessed.

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The Royal Borough of Kensington and Chelsea

The Borough of Hackney

The London Borough of Lewisham

The Corporation of London

The Rural District Council of Epping and Ongar.

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TABLE 2

KEY:

C	Corrected mean SO_2 μ g/m^3
dd	Wind direction
C/c̄	Concentration normalised by mean conc. for wind direction
t$_{calm}$	Hours $V \leq 2$ kt
v̄	Mean wind speed (kt)
T$_{min}$	Minimum temp (^{o}C)
MRMD	Mean reciprocal mixing depth
F/C	Forecast and success (see text)

Date		C	dd	C/c̄	t$_{calm}$	v̄	T$_{min}$	MRMD	F/C
1968									
Oct	1	127	260	0.57	0	13	14	8	=
	2	104	240	0.51	0	13	15	2	=
	3	121	240	0.59	0	14	15	2	=
	4	198	260	0.89	4	9	16	3	=
	10	172	220	0.84	1	8	14	3	=
	11	123	240	0.60	0	13	12	4	=
	15	182	260	0.82	2	8	10	4	=
	16	174	230	0.85	0	12	11	2	=
	17	161	260	0.72	0	9	9	6	=
	18	314	250	1.41	13	7	8	5	Ax
	22	493	140	1.63	15	5	10	7	A=
	23	548	360	1.96	18	3	12	6	A=
	24	480	050	1.77	8	6	11	5	A=
	25	331	070	0.94	0	10	12	7	=
	29	253	190	1.08	0	12	12	4	=
	30	197	230	0.96	7	12	11	5	=
	31	204	180	0.76	7	8	14	7	=
Nov	1	202	200	0.86	2	12	13	6	=
	5	418	030	1.72	12	11	2	5	A=
	6	378	070	1.08	2	9	7	8	=
	7	311	070	0.89	2	14	7	6	=
	8	283	060	1.04	2	11	6	7	=
	12	546	150	1.81	11	6	4	6	A=
	13	506	110	1.28	0	10	4	7	x
	14	431	100	1.09	0	14	6	4	x
	15	394	090	1.12	0	17	5	5	=
	19	284	340	1.02	3	10	6	6	=
	20	425	320	1.21	20	5	7	6	A=
	21	382	150	1.26	5	8	7	10	=
	22	317	160	1.18	1	9	6	8	Ax
	26	225	190	0.96	0	12	10	5	=
	27	250	190	1.06	2	11	12	10	=
	28	585	120	1.48	17	6	7	7	A=
	29	529	030	2.18	12	4	8	9	A=

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Date	C	dd	$C/\sqrt{c}$	t_{calm}	$\bar{v}$	T_{min}	MRMD	F/C
Dec 3	892	080	2.54	12	7	2	9	B=
4	443	160	1.65	10	5	4	6	Bx
5	303	150	1.00	2	6	4	6	=
6	481	140	1.59	12	8	1	7	A=
10	618	030	2.54	20	5	2	6	B=
11	374	050	1.38	1	6	3	6	=
12	469	340	1.68	16	7	4	10	A=
13	864	060	3.19	13	5	0	9	B=
17	419	220	2.05	7	9	0	6	A=
18	300	180	1.12	2	10	6	5	=
24	278	270	1.25	3	13	6	10	=
31	570	330	1.76	12	7	0	7	A=
1969								
Jan 1	677	340	2.43	17	7	2	8	B=
2	565	270	2.53	2	8	0	9	A=
3	499	330	1.54	14	8	5	7	A=
7	500	090	1.42	0	10	1	6	x
8	346	150	1.14	0	14	6	4	=
9	435	190	1.85	10	12	2	7	A=
10	421	120	1.06	0	8	2	8	A=
14	321	190	1.36	0	16	8	5	=
15	271	190	1.15	0	13	4	6	=
16	287	170	1.07	3	10	4	4	=
17	248	270	1.11	1	13	3	3	=
21	290	150	0.96	0	8	6	6	=
22	319	190	1.36	0	12	10	7	=
23	351	230	1.72	8	10	11	8	A=
24	281	240	1.38	13	5	10	10	Ax
28	274	200	1.16	0	12	7	7	=
29	353	270	1.58	9	8	3	8	A=
30	341	270	1.53	1	8	4	8	A=
31	197	240	0.96	0	14	7	3	=
Feb 4	449	340	1.61	4	14	-1	4	A=
5	670	280	2.89	17	6	-1	9	B=
6	706	280	3.04	16	4	4	10	B=
7	329	240	1.61	0	6	2	5	A=
11	635	320	1.96	5	9	-3	7	B=
12	318	V	1.03	0	11	1	6	=
13	233	360	0.83	0	14	0	4	=
14	503	360	1.80	15	11	-1	8	A=
18	379	360	1.36	5	9	-1	7	=
19	409	050	1.51	0	10	0	5	x
20	346	050	1.28	0	21	-1	9	=
21	475	180	1.77	1	13	2	6	x
25	591	060	2.18	9	10	6	8	A=
26	381	040	1.40	0	6	4	6	=
27	276	030	1.13	0	9	0	6	=
28	289	350	1.03	0	11	2	4	=
Mar 4	387	360	1.39	0	11	3	6	=
5	396	040	1.46	0	14	0	5	=
6	396	050	1.46	0	14	1	9	=
7	581	150	2.14	12	8	-3	6	A=
11	552	080	1.57	0	13	4	5	x
12	399	V	1.30	0	11	3	7	=
13	525	070	1.50	0	10	3	6	x

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Date	C	dd	C/c̄	t_{calm}	$\bar{v}$	T_{min}	MRMD	F/C
Mar 14	216	220	1.06	1	12	8	6	=
18	472	070	1.34	0	10	6	8	A=
19	498	070	1.42	0	10	6	10	A=
20	369	020	1.52	2	6	5	7	x
21	372	010	1.53	4	2	5	7	x
25	280	360	1.00	0	10	1	3	=
26	251	030	1.03	0	10	2	2	=
27	171	030	0.70	0	12	1	2	=
28	280	050	1.03	4	12	1	5	=
Oct 1	175	280	0.75	4	3	7	4	=
2	235	310	0.73	9	4	3	7	Ax
3	165	250	0.74	0	7	12	8	=
7	195	220	0.95	2	3	15	8	=
8	149	210	0.63	2	7	15	5	=
9	255	200	1.08	14	5	10	5	Ax
10	380	130	1.26	19	1	7	4	Ax
14	207	120	0.52	1	5	14	4	=
15	177	240	0.97	2	7	9	6	=
16	197	190	0.84	1	7	10	5	=
17	255	160	0.95	11	6	8	8	Ax
21	328	170	1.22	19	1	9	4	Ax
22	429	040	1.58	17	1	12	4	A=
23	301	250	1.35	12	2	11	9	Ax
24	126	250	0.56	0	7	13	4	=
28	333	270	1.50	15	2	5	5	A=
29	223	200	0.95	4	3	10	5	=
30	263	340	0.94	7	7	5	8	Ax
31	205	280	0.88	0	6	9	2	=
Nov 4	135	230	0.66	0	17	14	2	=
5	224	300	0.96	2	11	5	8	=
6	417	270	1.87	13	4	-2	6	A=
7	296	160	1.10	4	3	5	6	=
11	248	230	1.21	0	9	8	6	=
12	163	180	0.61	2	14	12	3	=
13	192	220	0.94	0	10	6	2	=
14	379	210	1.61	16	4	0	7	A=
18	461	290	1.99	9	8	-2	8	A=
19	292	210	1.24	0	8	2	6	=
20	161	230	0.79	0	11	10	3	=
25	320	320	0.99	0	10	1	2	=
26	280	310	0.87	0	12	1	3	=
27	395	320	1.22	1	9	-1	9	Ax
28	287	240	1.41	0	8	5	7	=
Dec 2	529	230	2.59	1	4	2	9	A=
3	356	230	1.74	0	7	5	6	x
4	218	280	0.94	0	9	4	4	=
9	661	330	2.05	6	7	1	6	x
10	1161	V	3.78	24	1	3	10	B=
11	632	170	2.36	13	1	0	10	B=
12	357	180	1.33	2	4	6	6	=
16	304	260	1.36	0	12	3	3	=
17	421	340	1.51	7	6	-1	8	A=
18	411	060	1.52	0	13	1	3	x
19	463	020	1.90	10	9	-2	6	A=
23	320	290	1.30	0	12	6	9	=
24	318	230	1.56	0	5	4	8	A=
30	428	090	1.22	0	12	0	4	x
31	265	040	0.98	0	17	0	4	=

Date		C	dd	$C/\sqrt{c}$	t_{calm}	$\bar{v}$	T_{min}	MRMD	F/C
1970									
Jan	1	215	030	0.88	0	16	−1	5	=
	2	387	V	1.26	0	9	−1	4	=
	6	453	270	2.03	1	4	−4	9	A=
	7	556	270	2.49	7	9	−2	8	Bx
	8	659	C	2.15	4	4	−5	10	B=
	9	438	090	1.25	0	13	−2	5	A=
	13	284	170	1.06	5	9	5	8	Ax
	14	249	140	0.82	0	7	8	5	=
	15	232	140	0.77	2	10	8	5	=
	16	283	130	0.94	8	4	8	7	=
	20	178	130	0.59	0	8	7	7	=
	21	286	160	1.07	7	5	7	9	=
	22	250	160	0.93	2	9	8	6	=
	23	295	190	1.25	3	5	3	9	Ax
	27	423	230	2.07	11	3	4	8	A=
	29	399	120	1.01	0	6	3	7	=
	30	257	100	0.65	0	11	5	6	=
Feb	3	173	230	0.85	0	13	7	4	=
	4	278	250	1.25	0	12	4	3	=
	5	277	230	1.36	5	9	3	3	=
	6	317	350	1.14	1	7	2	6	=
	10	197	250	0.88	0	11	2	7	=
	11	421	270	1.89	9	8	−4	7	A=
	12	505	V	1.67	3	4	−1	8	Bx
	13	318	030	1.31	2	16	1	6	=
	17	366	300	1.58	6	8	−3	10	A=
	18	253	270	1.13	0	13	3	2	=
	19	243	230	1.19	0	9	4	2	=
	20	158	220	0.77	0	12	8	3	=
	24	247	250	1.11	0	8	6	3	=
	25	269	290	1.16	2	9	3	5	=
	26	307	330	0.95	5	5	1	5	=
	27	239	350	0.86	0	9	2	3	=
Mar	3	262	320	0.81	0	10	−1	3	=
	4	354	300	1.52	0	8	−1	5	x
	5	340	V	1.11	0	11	0	6	=
	6	447	320	1.38	0	7	−1	6	x
	10	683	V	2.22	12	3	−1	9	B=
	11	495	210	2.11	1	4	1	6	A=
	12	444	200	1.89	3	8	3	8	A=
	13	429	070	1.22	0	8	2	2	x
	17	231	280	0.99	0	7	7	5	=
	18	240	240	1.18	0	11	10	4	=
	19	189	270	0.85	0	13	5	2	=
	20	212	270	0.95	0	11	7	9	=
	24	282	V	0.92	3	5	6	3	=
	26	314	010	1.29	8	7	−1	5	Ax

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APPENDIX

Estimation of SO_2 daily concentrations in non-urban situations

1.   A study has been made of the SO_2 daily concentrations during 1969 at Kelvedon Hatch.   The geographical position of Kelvedon Hatch, the neighbouring towns and the concentration rose are shown on Figure 12.

Meteorological data from Stansted, (standard meteorological data) and from Cardington (Balthum data) have been examined to see whether or not the daily concentration levels could be, in part at least, explained in terms of the current weather situation.   This note explains the conclusions of this study.

2.   The significance of the weather at Stanstead and Cardington to Kelvedon Hatch

(i)   Stanstead is about 22 km away to the NNW;   Cardington is 67 km to the NW.

(ii) There will almost certainly be differences in the relevant weather conditions at the three sites although these should not normally be large. No other suitable meteorological station lies closer to Kelvedon Hatch.

3.   The correlation of concentration values at Kelvedon Hatch and other measuring sites

(i)   Different sites may be shown to have different concentration-roses and this is presumably due to the different positioning of SO_2 sources.

(ii) The validity of any concentration forecasting scheme is limited by "random" differences between sites:

SITE 1	SITE 2	DISTANCE APART	CORRELATION
Kelvedon Hatch	Mountnessing	8 km	0.7
Sibton	Framlingham	9 km	0.27 (both rural sites)
Market Rasen	Kirkby Underwood	60 km	0.59
Kelvedon Hatch	Kirkby Underwood	140 km	0.53 (west winds)
Kelvedon Hatch	Market Rasen	190 km	0.53 (west winds)
Sibton	Kirkby Underwood	140 km	0.13

TABLE A.1

The table gives typical values of the correlation between concentrations recorded on the same days at two sites.

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Note: (a) Sibton seems poorly correlated with other sites

(b) The correlation falls rapidly with distance to a value between 0.5 and 0.6 and then remains fairly steady.

This behaviour suggests two sources of "error":

Error 1: errors in the values themselves due to the inherent inaccuracy of the measuring technique. Also included may be the influence of one or more close-by sources whose contributions to the readings may not depend on the stability in the expected way. (e.g. a nearby chimney may give larger contributions in unstable conditions than in stable conditions due to its elevation.

Error 2: errors arising from geographical variations in the weather.

Error 1 would account for correlations significantly less than unity between sites almost irrespective of their separation, whereas Error 2 gives a scale of "weather" correlation of the order of several hundred kilometres.

4. A summary of the variables required for prediction of concentration

(1) The local concentration-direction rose.

(2) The mean wind direction for the day.

(3) The "mean" temperature for the day (i.e. the mean of the temperatures at 09Z, 12Z, 15Z, 18Z, 21Z and 24Z as measured at Stanstead or estimated to apply at the site).

(4) The cloud amounts (in eighths) and the wind speed in knots at these same hours.

(5) Knowledge of low-level inversions and low-level cloud heights.

Briefly the method runs as follows:

(a) The cloud amounts are used in conjunction with Cambridge analysed radiation data, time of day and month to estimate whether the daytime insolation is

STRONG INSOLATION

MODERATE INSOLATION

SLIGHT INSOLATION

(see Figure 13).

(b) Pasquill's original scheme is then used, using the insolation and wind speed in knots to estimate a stability category: A to F. (see Table A.2)

(c) A typical SO_2 plume height is then associated with the deduced stability category (see Table A.3) which refers in practice to the height appropriate to a source at ground level at a standard 10 kilometres upwind.

(d) Inversion heights and cloud-base heights are used to give another estimate of plume height.

(e) Using an objective scheme (see later) a best estimate of the plume height is then obtained for each of the key hours (i.e. 09, 12, 15, 18, 21 and 24Z).   These are then combined by another objective process to give the MRMD (the weighted mean reciprocal mixing depth).

The lower the plume heights the higher is MRMD and vice versa.

(f) MRMD and the mean temperature are then used to give the expected normalised concentration (see Figure 14).   The normalised concentration is defined as the ratio of the actual concentration to the annual mean concentration for that mean wind direction (supposed known from the concentration direction rose).

5.   A summary of the results

The scheme has been applied to the concentration data for Kelvedon Hatch for 1969.   Since inversion data were required in the analysis and the Cardington Balthum ascents were the only nearby regular source of these, only those days when both concentration readings and 12, 18 and 24Z Balthum ascents were available could be used.   This requirement reduced the number of useable days to 137.

The concentration direction rose was obtained from all days in the year for which concentration values were available.

The analysis has the following points:

(1) Since the predictive numbers, scoring scheme, etc, are deduced from the 1969 data itself, another year might give slightly poorer results.

(2) Post-facto data of cloud amounts, wind speeds etc have been used. In any operational forecasting scheme these data would have to be forecast with the usual introduction of error adding to the uncertainty of the estimated concentration values.

The normalised concentrations range from 0.37 to 2.94 with a standard deviation of approximately 0.5 about the mean 1.04.   Application of the scheme reduces the standard deviation to about 0.15 (i.e. by a factor 0.313).   This is a very significant improvement in view of all the possible sources of error.

Figure 14 shows how MRMD and the mean temperature are combined to give the normalised concentration.   Mean temperature is a significant parameter possibly since sources of pollution may be temperature sensitive.   The output from power stations, domestic chimneys and other heating appliances are all likely to increase as the temperature drops.

6. The radiation figures

Cambridge radiation data for the years 1961-64 have been analysed according to the month, time of day and cloud amounts.

Figure 13 shows values of the total radiation on a horizontal surface expressed in milliwatts per square centimetre ranging from 0 to nearly 100. Curves are drawn for each month against time of day showing:

(i) The maximum value recorded during the years studied

(ii) The mean values for the following cloud amounts (in eighths)

0-1	:	virtually clear skies
2	:	some cloud
3-5	)	fairly cloudy
6	)	
7-8	:	very cloudy

It is interesting that the biggest changes occur

(a) between the first two categories: presumably a water vapour absorption effect

(b) between the last two categories: direct radiation from the sun reaching the surface through gaps in the clouds is virtually eliminated in passing from $^6/8$ths to $^7/8$ths cloud.

According to Pasquill "strong insolation" corresponds to sunny midday in midsummer in England.   We decided that our definition of strong insolation should include 90% of all such cases.   This led to the definition:

Strong insolation: total radiation $\geq$ 60 milliwatts/cm^2.

Similarly "slight insolation refers to similar conditions in midwinter" gave:
Slight insolation: total radiation $\leq$ 30 milliwatts/cm^2.

Moderate insolation therefore refers to all total radiation values between 30 and 60 mw/cm^2.

7. Pasquill Stability Categories

Table A.2

WIND SPEED (kts)	Daytime (excluding 1 hr to sunrise or set)				Within 1 hour of sunrise or sunset	Night-time		
	Insolation					Cloud amount		
	Strong	Moderate	Slight	Overcast		$\leq \frac{3}{8}$	$\geq \frac{4}{8}$	$8/8$
4	A	A–B	B	C	D	F	F	D
4–6	A–B	B	C	C	D	F	E	D
6–10	B	B–C	C	C	D	E	D	D
10–12	C	C–D	D	D	D	D	D	D
> 12	C	D	D	D	D	D	D	D

Table A.2 gives the key to the stability categories almost exactly as defined by Pasquill. The categories run from A, the most unstable, to F, the most stable.

8. Plume height

"Plume" refers here to a supposed cloud of pollution, which may, or may not have the same height as the conventional water clouds. It is supposed that the "typical" source affecting the sampling point lies some 10 kilometres upwind. Not all sources will of course be this distance away, some will be nearer, some further away, but it is tentatively postulated that an effective plume height derived on this assumption is meaningful in terms of the composite pollution cloud derived from all the sources.

From Pasquill's vertical spread curves ("Atmospheric Diffusion" p.209) the following values are obtained:

Table A.3

Stability Category	Plume height, h_D, in metres
A	5000
B	3000
C	1000
D	350
E	180
F	100

9. Inversions and water clouds

The Cardington Balthum ascents frequently indicated the presence of an inversion. If the inversion base is at h_I metres above the ground, the inversion will provide an effective lid to the diffusion of the pollution cloud, and provided the cloud has extended up to the inversion base within 10 km, h_I should

replace the plume height h_D as given in the last section.

For surface inversions h_I is taken as 50 metres (although see the rules set out in the following section).

If water-cloud heights are known these should also be taken into consideration as indicating a possible level to which diffusion of the pollution may have occurred.   We call the water-cloud height h_C.

Thus up to three heights are available to indicate the pollution cloud height h_p:

h_D ..... height as indicated by Pasquill Stability Category

h_I ..... height as indicated by Inversion base

h_c ..... height as indicated by the observed cloud base.

10.   Rules for estimating h_p

Rule 1.   The following <u>minimum</u> cloud heights were found to avoid incongrous results:

At 09Z and *18Z .... 150 metres

At 12Z and 15Z .... 300 metres

At 21Z and 24Z .... 50 metres

* except for Nov.-Feb. when 50 metres is taken.

Thus if h_p is less than these it is replaced by the minimum height.

Rule 2.   With fog, select the minimum cloud height as defined in Rule 1.

Rule 3.   If $h_I \leqslant (h_D, h_C)$ select h_I, modified if necessary by Rules 1 and 2.

Rule 4.   If h_I is not given or if $h_I > (h_D, h_C)$ then h_C is selected if available provided:

$h_C < h_D$ appropriate to a stability category <u>one category more unstable</u> than that indicated

e.g.   suppose category D is indicated by Section 7 and h_C is 500 metres then, although $h_D(D) = 350$ metres and $h_C > h_D(D)$, if the category is upgraded by one to C: $h_D(C) = 1000$ metres.   Now $h_C < h_D$ and so is accepted as the best estimate of h_p.

Rule 5.   At 09Z, or at other times with only slight insolation, if the cloud heights h_p are significantly smaller at the neighbouring times, the value of h_p is revised to fit in with its neighbours as follows: The stability category under these conditions is not allowed to exceed one category above the higher of its neighbours:

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e.g. D A-B C sequence would be modified to D B C

If h_C dominates h_D, continuity of h_C should be expected.

11. Weighted mean reciprocal mixing depth: MRMD

Values of h_p are available using the methods described above at 09, 12, 15 18, 21 and 24Z.   The aim has been to combine these in a way that will best estimate the pollution recorded over 24 hours at the sampling point and measured the following morning.

The measurements of SO_2 (i.e. cumulative dosages since the last measurement) are made at times that seem to vary from day to day and from sampling site to sampling site.   A fairly typical time may be taken as 10Z.

It is assumed that at a fairly rural site like Kelvedon Hatch comparatively little contribution to the day's total is made during these early morning hours. The pollution generated that morning then only significantly affects the sampler after the morning readings have been made, and therefore contributes to the reading of the following morning.

The source-strength of the SO_2 pollution is likely to show a typical diurnal variation and therefore it is reasonable to weight the values of h_p, according to the time of day, in combining them to form MRMD, the mean reciprocal mixing depth.   The weightings were determined by careful examination and a trial-and-error process for one wind direction.   They are consistent with the idea that the source strengths will be greatest during the day and least at night.

The following definition of MRMD has been used:

$$\frac{(MRMD)}{100} = \frac{1}{2h_p(09Z)} + \frac{8}{h_p(12Z)} + \frac{8}{h_p(15Z)} + \frac{1}{h_p(18Z)} + \frac{1}{h_p(21Z)} + \frac{1}{2h_p(24Z)}$$

12. An example of the determination of MRMD

The 14th July 1969 illustrates the method quite well:

Time:	09Z	12Z	15Z	18Z	21Z	24Z
Cloud Amount ($\frac{1}{8}$ths)	0	3	2	0	0	0
Wind Speed (kts)	5	7	6	12	7	6
Cloud base (metres) h_c	-	1200	1200	-	-	-
Temperature (^{o}C)	21.4	25.2	25.7	22.9	17.0	14.8
Insolation	Str./Mod.	Mod.	Mod.	Slight	-	-
Uncorrected Stability Cat.	A-B	B-C	B	D	E	E-F
Inversion height	-	-	-	-	-	Surface
h_I (metres)	-	-	-	-	-	50
h_D (metres)	4000	2000	3000	350	180	100
h_p (metres)	1200	1200	1200	350	180	50

TABLE A.4   MRMD = 3.22

Mean temperature = 21.2, Mean wind direction = $(120° - 150°)$

Average SO_2 concentration for the day = $48 \, \mu g/m^3$

Average concentration for this wind direction = $80 \, \mu g/m^3$

Actual normalised concentration = $^{48}/_{80} = 0.6$

Predicted normalised concentration = 0.67

At 12Z and at 15Z on the 14th July, the cloud base provides the best estimate of h_p according to the rules. At 09Z no cloud is observed and h_D is the only contender. However on the basis of Rule 5, h_D seems too large, especially in view of the later cloud at 1200m. Thus h_p at 09Z is taken as 1200m. At 18Z and 12Z, the values of h_D are accepted for h_p. At 24Z the surface inversion is all important and h_p takes the standard value of 50 metres.

The definition in the last section gives MRMD = 3.22. Figure 14 uses MRMD = 3.22 and mean temperature = 21.2 to give a predicted normalised concentration of 0.67. Since the _mean_ concentration for the wind direction of July 14th is $80 \, \mu g/m^3$, the predicted concentration is $54 \, \mu g/m^3$. The actual concentration recorded is $48 \, \mu g/m^3$, the difference being well within the accepted margin of error of the sampling device.

13. Effect of temperature

It became clear that MRMD alone did not provide an adequate estimate of pollution concentration. On average, cold days had higher concentrations than warm days. Grouping the normalised concentrations into bands of MRMD and mean temperature revealed a strong dual dependence. Figure 14 is the outcome of this study. Section 5 has already discussed the main points.

14. Conclusions

The scheme has proved quite satisfactory on a post-facto basis reducing the standard forecasting error for the normalised concentration by as much as 70%.

It has yet to be shown

(i) that the scheme can be usefully applied on a forecasting basis

(ii) to be applicable to other non-urban sampling sites.

The rules for estimating whether or not a surface inversion exists in terms of wind speed and cloud amount are the same as those given in Section 3 of the main paper, with the additional rider that at 18Z between April and August: no inversions.

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A modified forecasting scheme for Inner London

A later development of the work on sulphur dioxide in London air has been the search for a practical method of predicting actual concentrations, as distinct from forecasting whether or not certain threshhold values are exceeded. The variation of concentration with the same meteorological parameters that were successfully used in the 'threshhold' method was studied for the two winter periods. The following fairly simple formula yielded reasonably satisfactory estimates of the average daily concentrations at the four sites :

$$C_{est} = \left[\frac{\bar{C}}{1+\delta_v} + \frac{C}{3}_p \right]\left[1 + \frac{\delta}{3}_d \right]\left[1 + \frac{\delta}{6}_m \right]\left[1 - \frac{T}{28} + \frac{t}{20} \right]$$

where $\bar{C}$ = long term mean concentration

$\quad C_{est}$ = estimated concentration (24-hour average)

$\quad C_p$ = concentration for the previous 24 hours

$\quad T$ = minimum temperature ($^\circ$C) expected up to midnight

$\quad t$ = number of hours of mean wind less than 3 knots during the 24 hours

$\quad \delta_v = \begin{cases} 1 & \text{if the mean wind for the day exceeds 6 knots} \\ 0 & \text{otherwise} \end{cases}$

$\quad \delta_d = \begin{cases} 1 & \text{if the mean wind comes from the 'dirty' sector, } 060^\circ \text{ to } 120^\circ \\ 0 & \text{otherwise} \end{cases}$

$\quad \delta_m = \begin{cases} 1 & \text{if the mixing depth is low (as defined at the end of Section 3)} \\ 0 & \text{otherwise} \end{cases}$

Although the formula has been verified only for the four sites, it is probably equally applicable to any group of sites in Inner London, and can possibly be applied to other cities provided the constants in the first three factors are suitably modified.

The formula can either be expressed graphically as a nomogram (see Figure 15) or it can be programmed for a desk electronic calculator (e.g. the Olivetti P 101 : the programme can be supplied on request).

The root-mean-square errors have been evaluated for the four sites over the two winters. The significance of the errors have to be assessed in relation to the inherent 'error' due to local quasi-random variations in concentration at the four sites which can be estimated from the inter-site correlation studies described in Section 4. The inherent error in the 4-site average concentration was shown to be about 50 $\mu g \, / \, m^3$.

The root-mean-square error in the formula-estimates is only 58 $\mu g \, / \, m^3$ (little more than the inherent error) if the actual value of C_p, the previous day's concentration is known and used, but rises to nearly 80 $\mu g \, / \, m^3$ when C_p is only known by the application of the formula using the _actual_ meteorological data at the end of the previous 24-hour day. This is still a satisfactorily small margin of error when compared with the inherent error.

If E_t is the total error, E_i is the inherent error, and E_s is the basic error of the scheme, then :

$$E_t^2 = E_i^2 + E_s^2$$

For the whole of Inner London (nearly 100 sites), E_i will fall from 50 $\mu g \, / \, m^3$ to about 10 $\mu g \, / \, m^3$. The expected value of E_t would then be

$$E_t^2 = (80)^2 - (50)^2 + (10)^2$$

i.e. a little over 60 $\mu g \, / \, m^3$.

The formula displays the relative importance of the basic parameters. It is clear that an error of $4^\circ C$ in T, the minimum temperature, would introduce an error in C_{est} of about only 50 $\mu g \, / \, m^3$. A similar error would follow from an error of 3 hours in t, the hours of light winds, or of about 150 $\mu g \, / \, m^3$ in C_p. The method does not therefore demand impossible precision in evaluating the basic meteorological parameters, and should prove to be operationally useful.
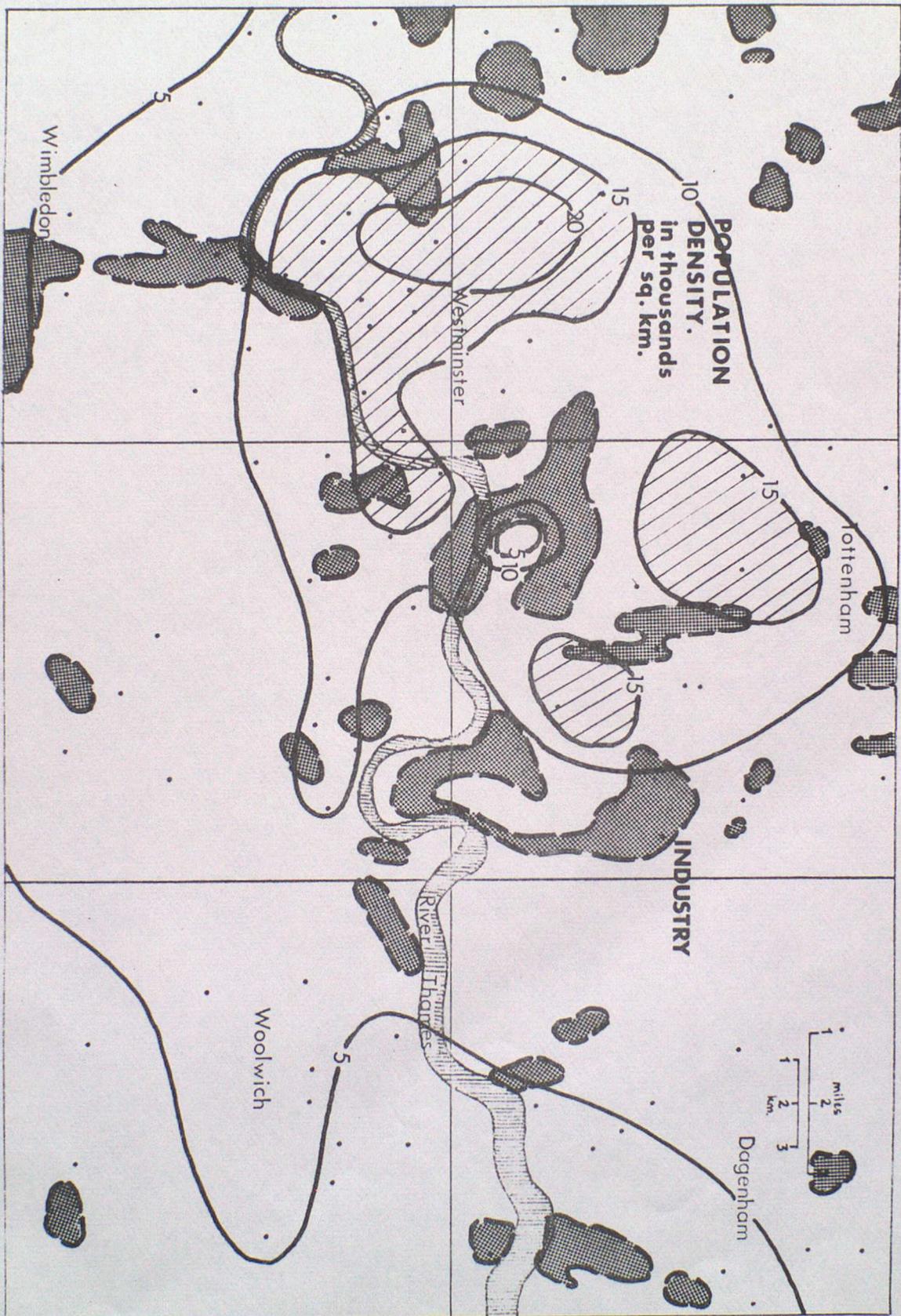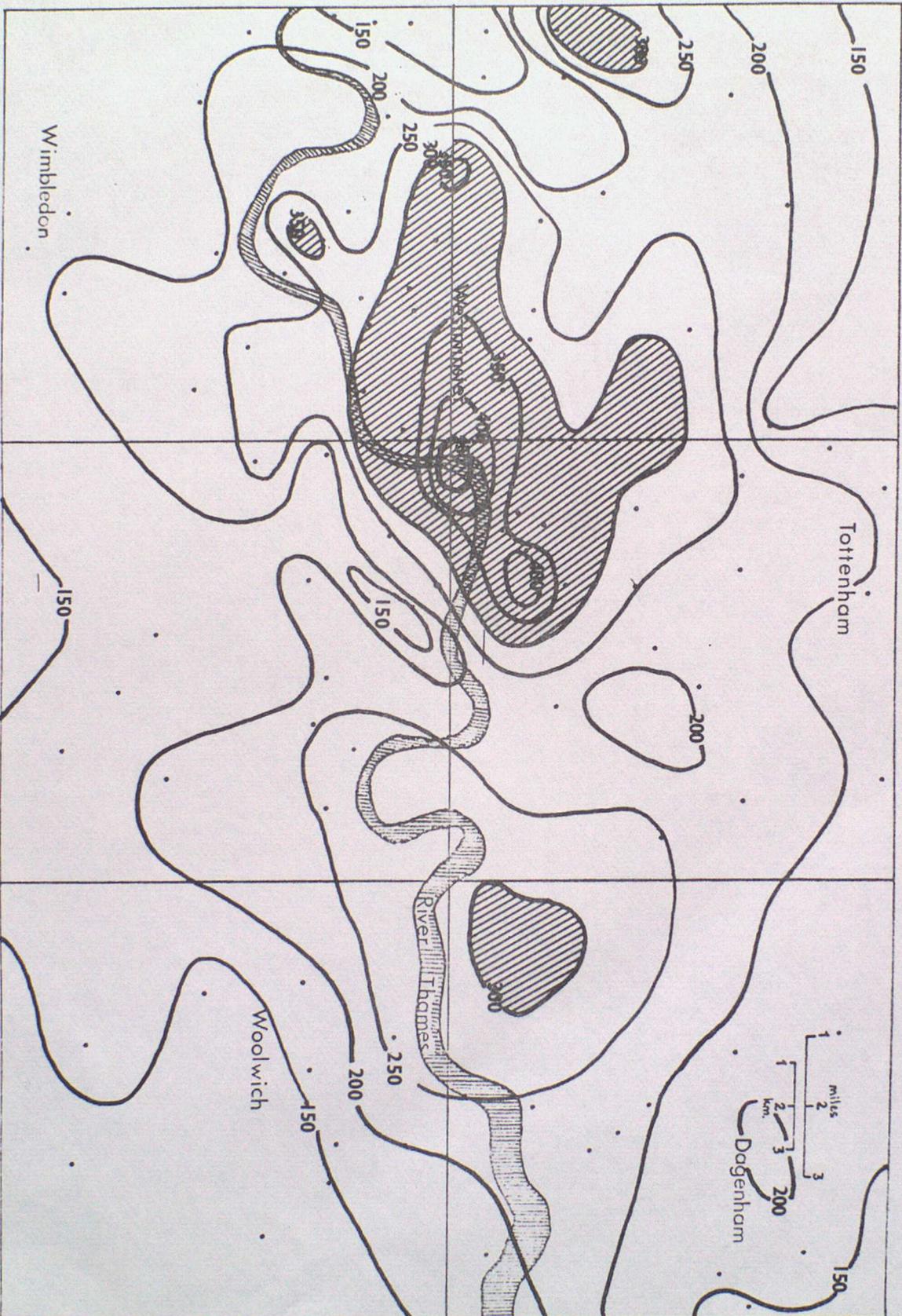
FIGURE 1

FIGURE 2   Mean winter concentrations for 1969–70 based on extrapolation from data of previous ten years. Sulphur dioxide — units : μg/m³
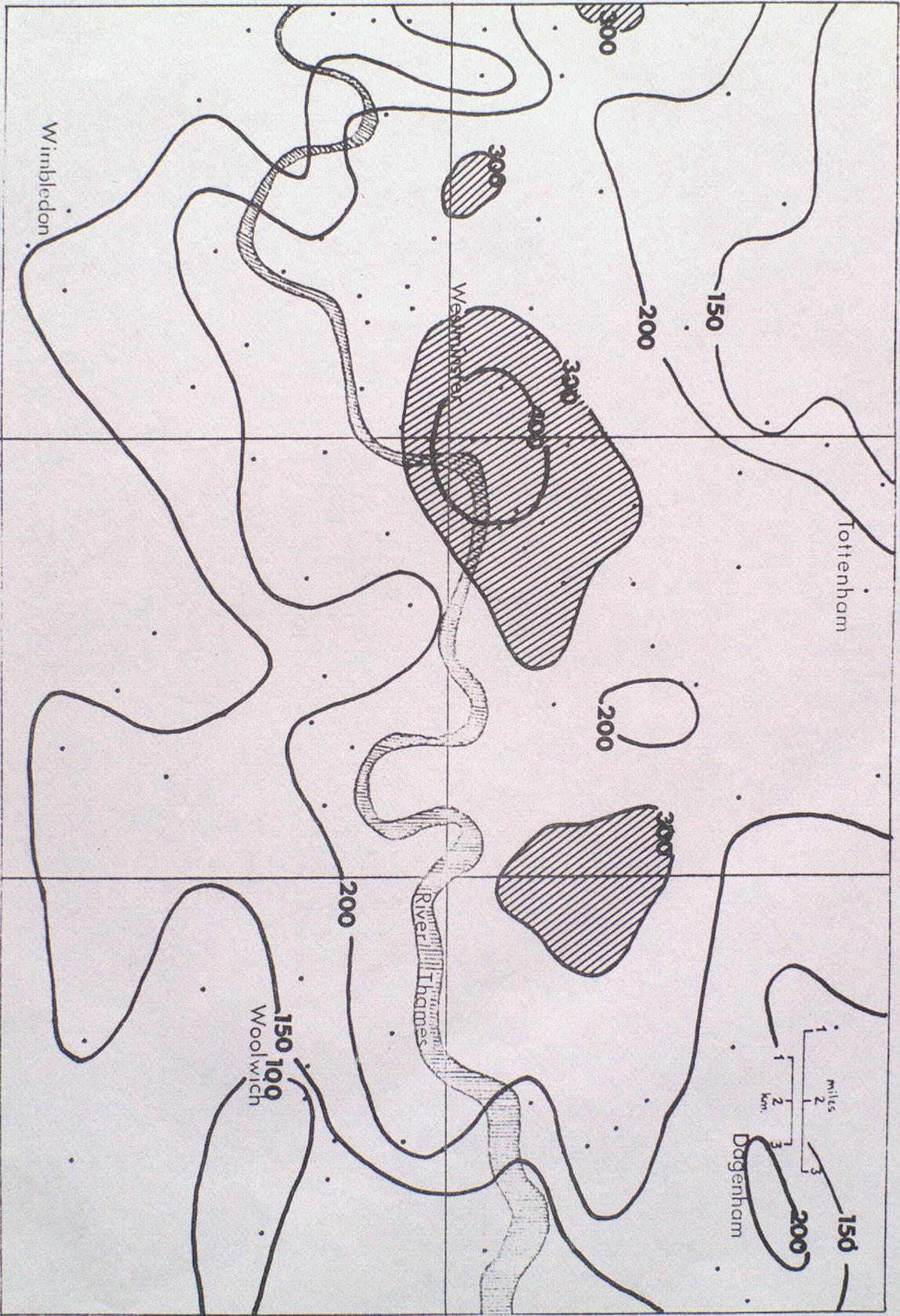
FIGURE 3   Mean   concentrations   for   winter   1966–67
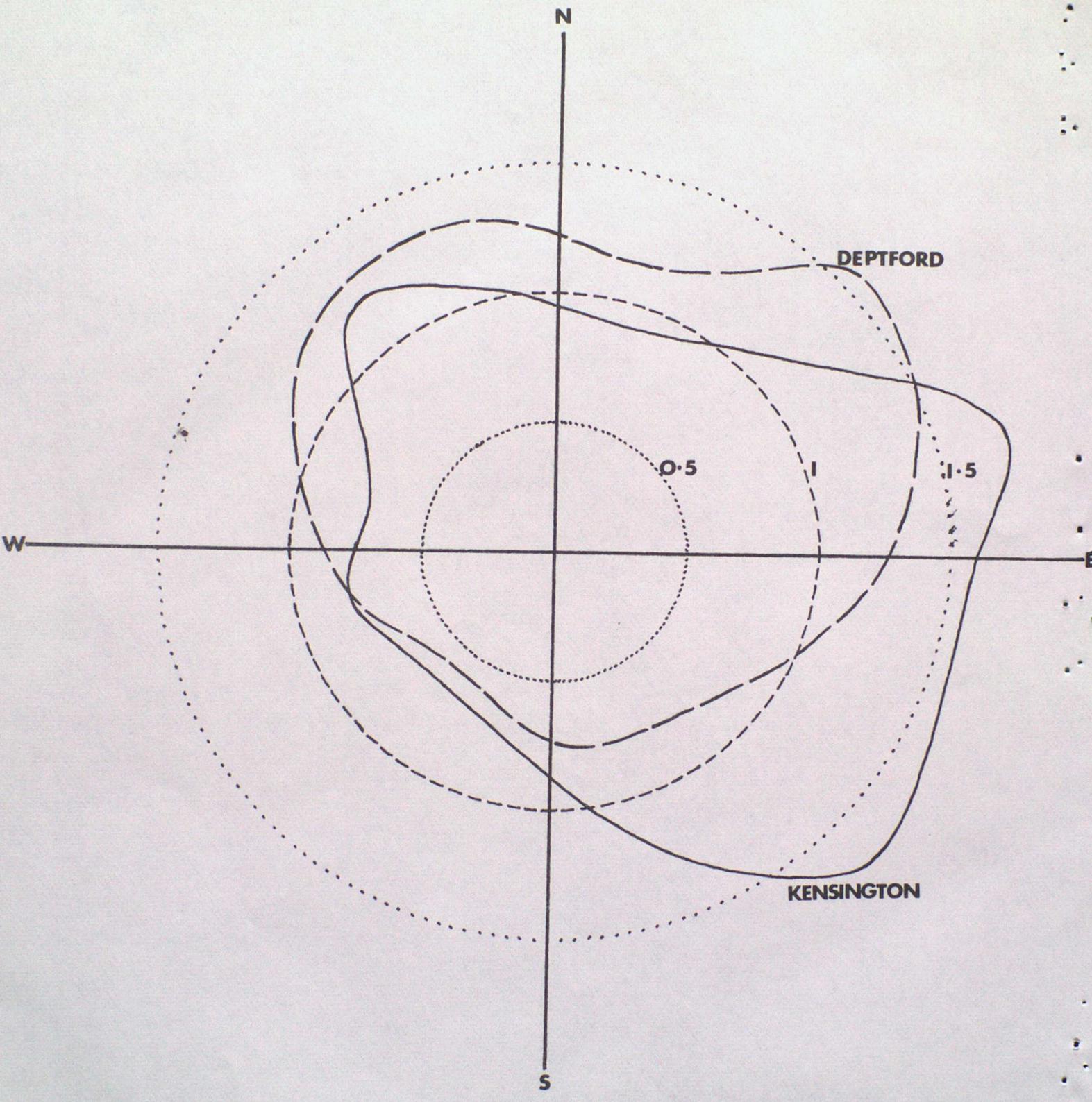
Normalised Concentration-direction roses for Kensington & Deptford

FIGURE 4

No. of cases

Frequency

Average Concentration μg/m³

Best-fit log-normal curve

Distribution Mean

Mean of the four stations

Histogram based on 290 values (mean winter concentrations) for all Inner London sites for the winters 1965-66 to 1969-70. Data grouped into 20 μg/m³ classes.
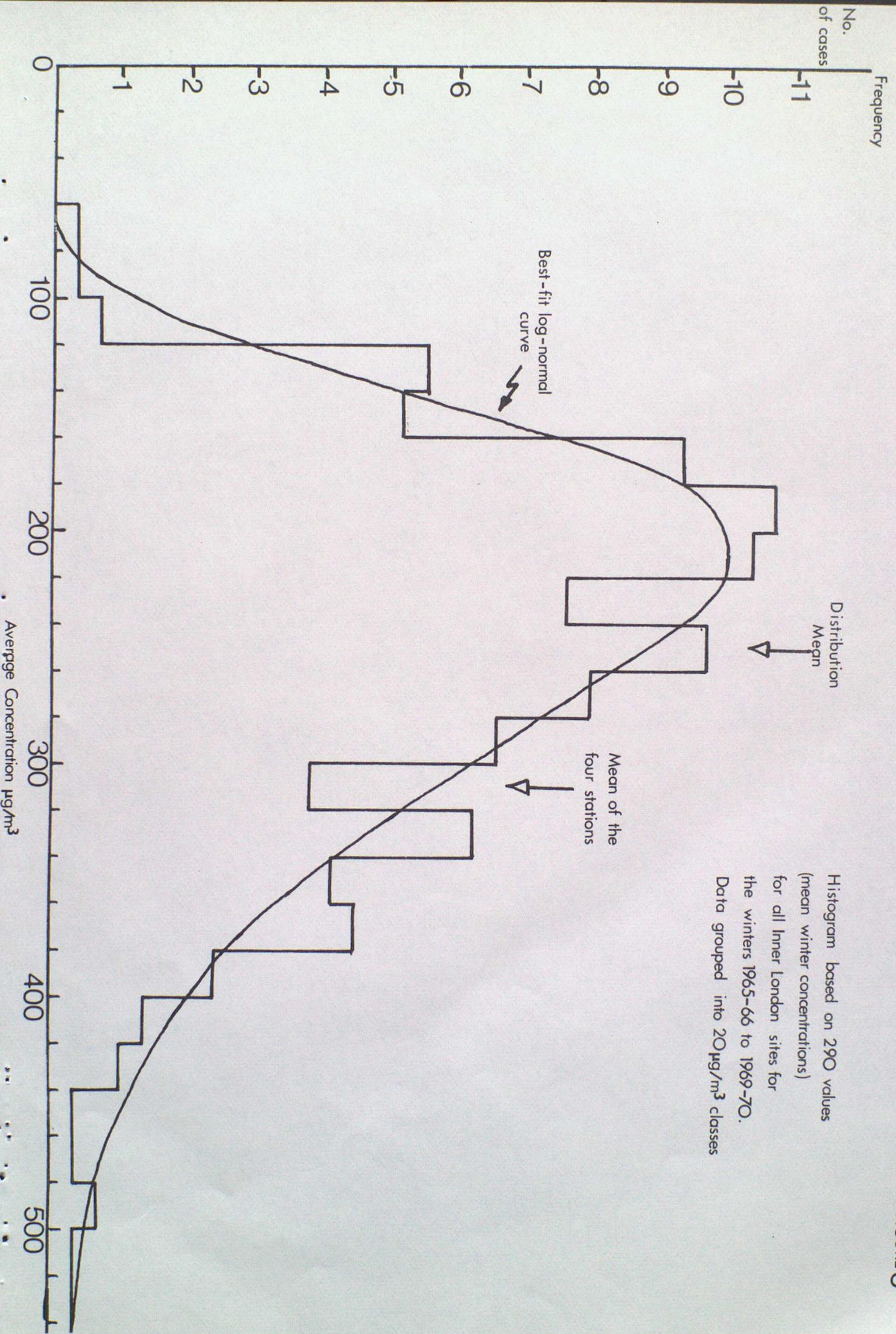
FIGURE 5

All winter concentrations 1965-66 to 1969-70 for the Inner London sites.

C median = 235
C mean = 250
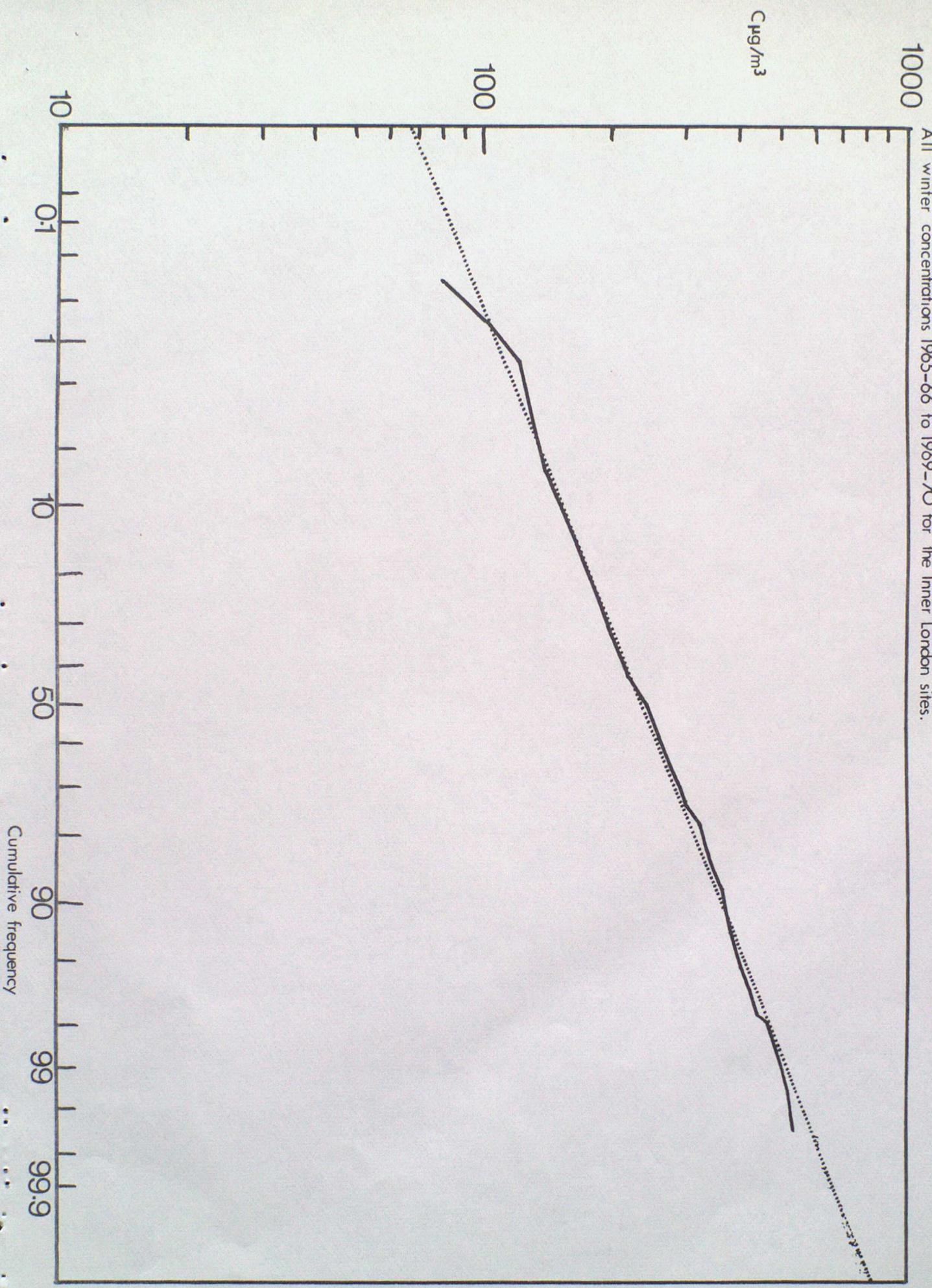
FIGURE 6

SPATIAL DISTRIBUTION

Mean winter 1965-70   All Inner London sites

Cμg/m3

C median = 227
C mean = 239
σ$_{ln c}$ = 0.313
σ$_c$ = 74.6

Cumulative frequency

FIGURE 7

Cµg/m³

Daily values average over the 4 sites   Winters 1968-69 & 1969-70

Cumulative frequency

Cmedian = 320
Cmean = 351
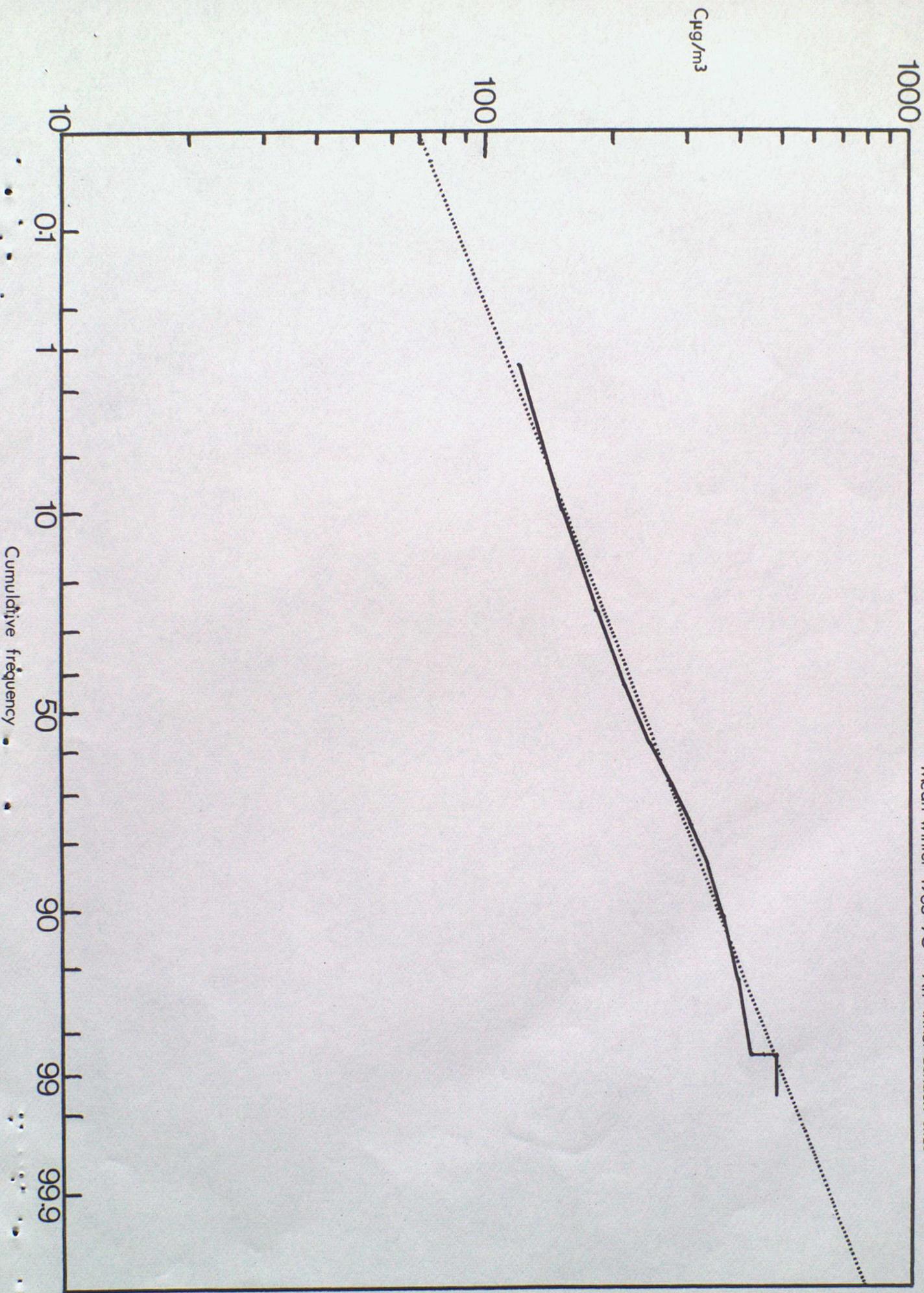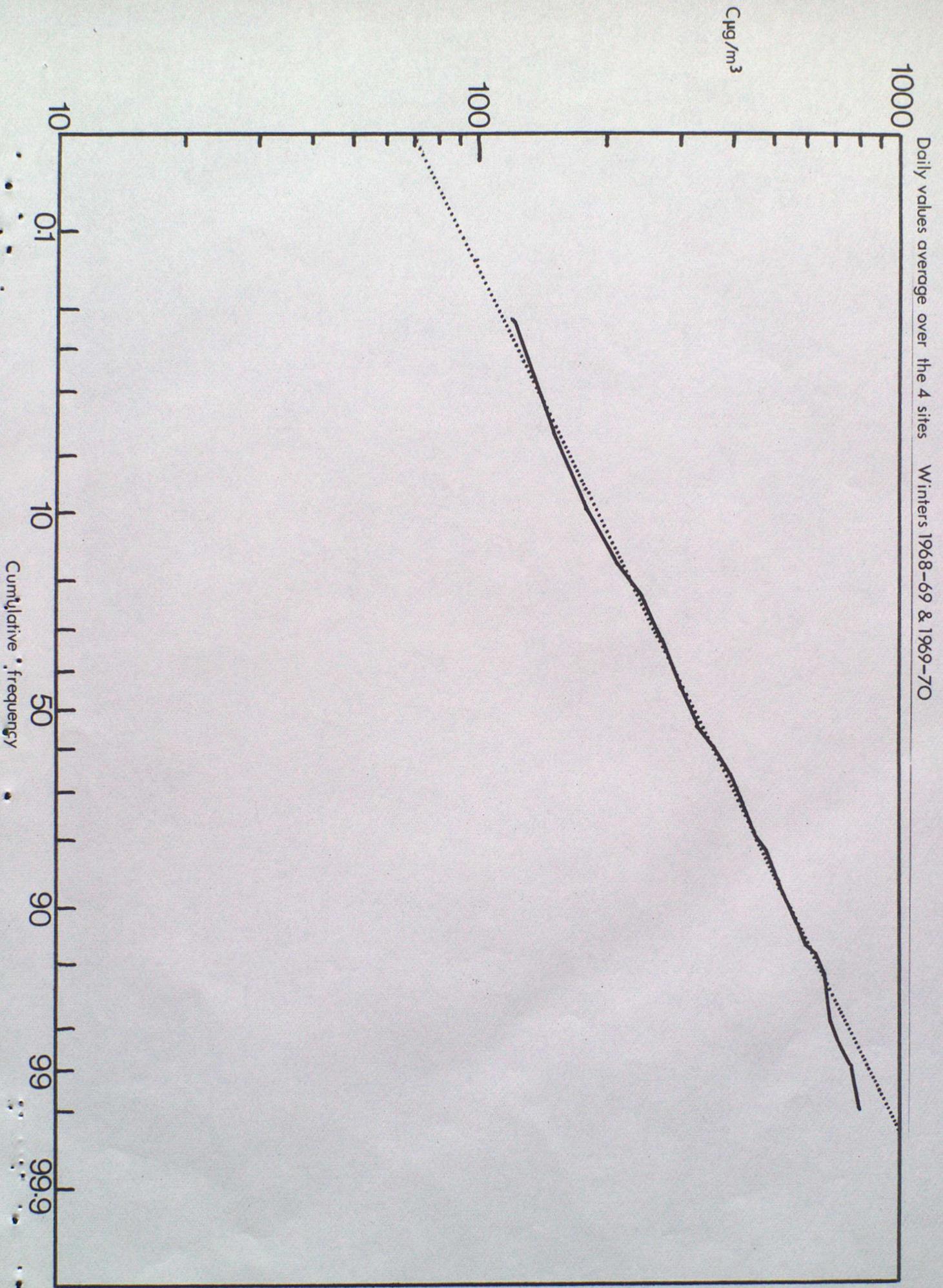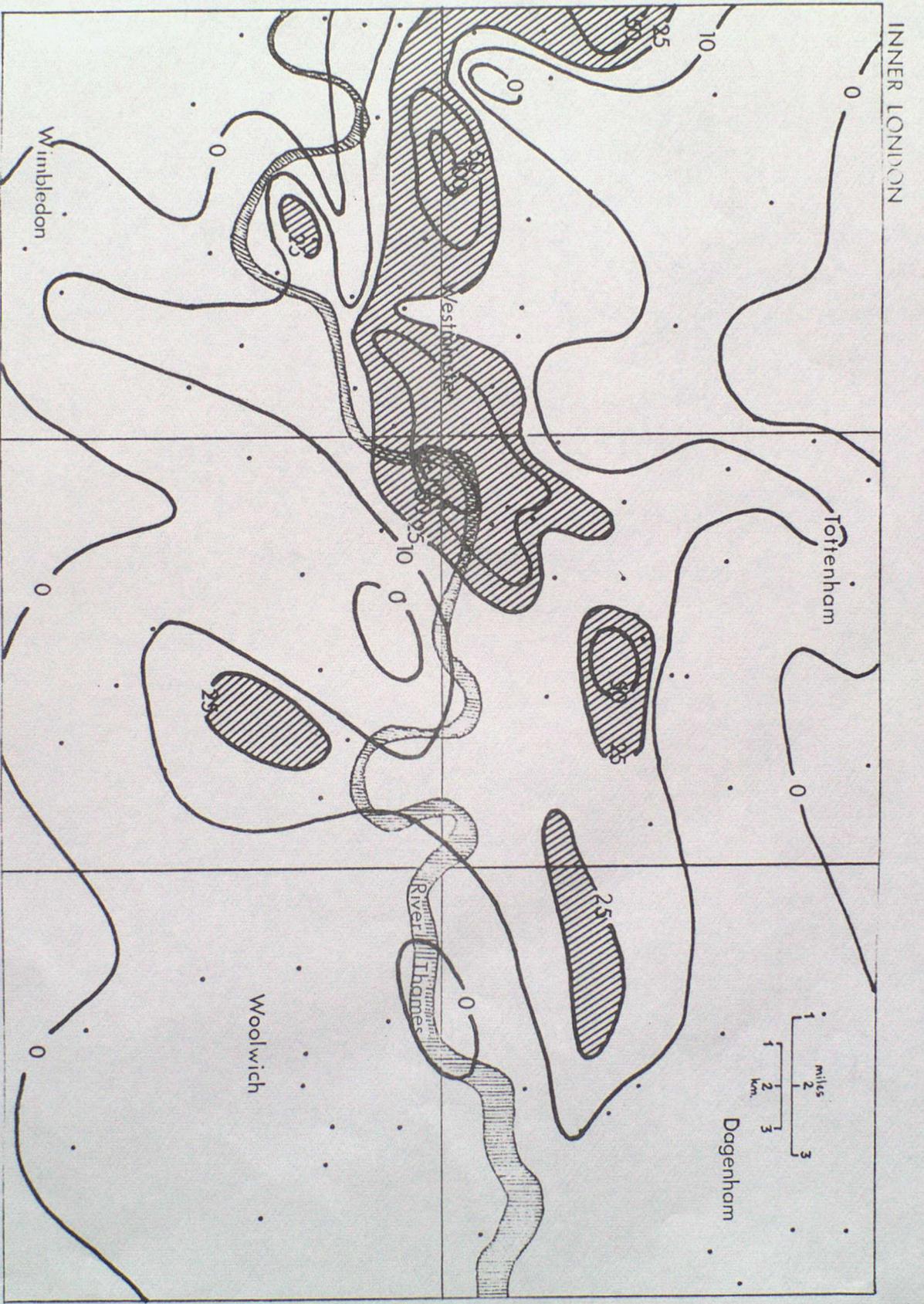
FIGURE 8

FIGURE 9   NUMBER OF DAYS WHEN $\bar{C}$ ⩾ 500   for the winters 1968-69 & 1969-70
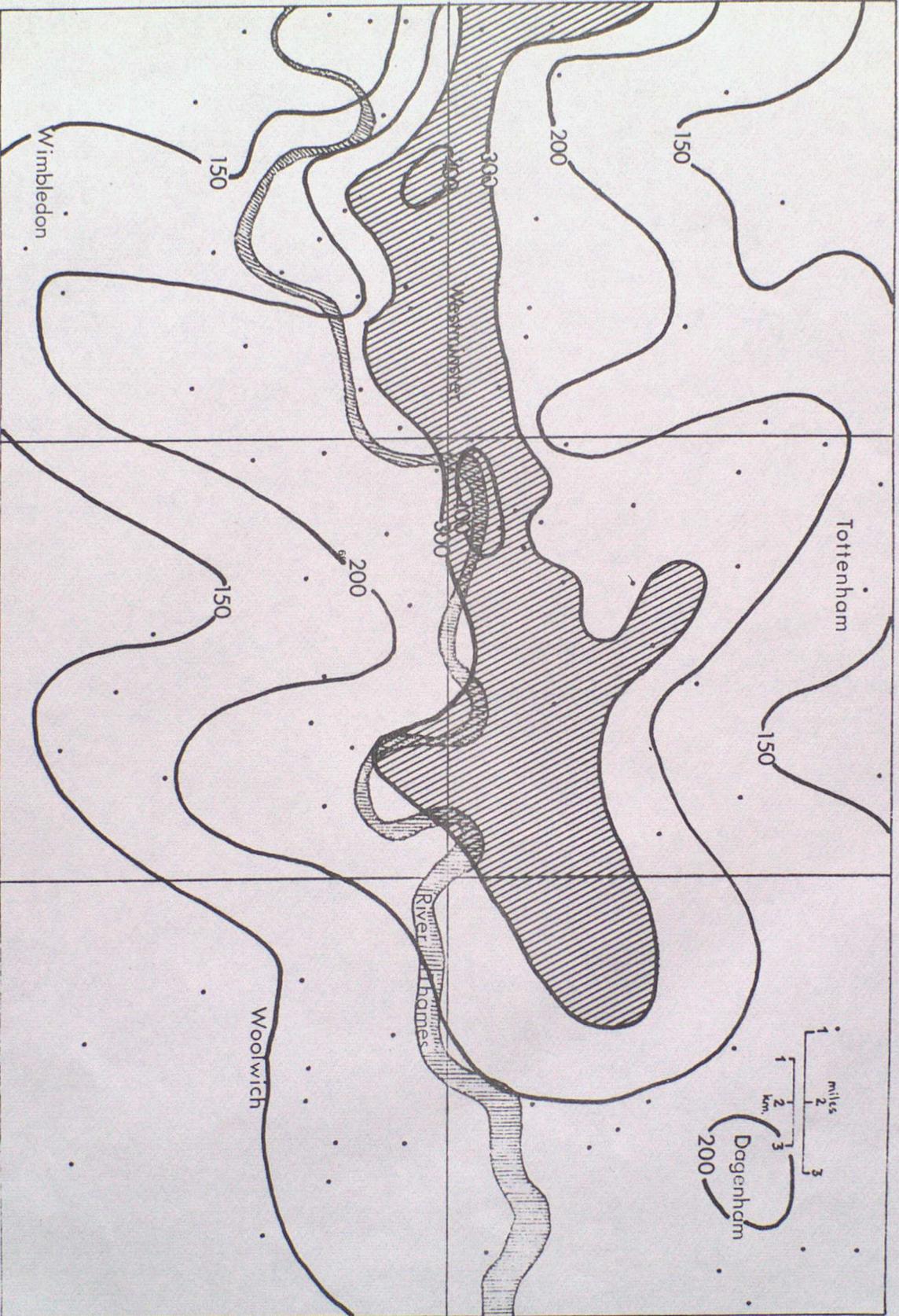
FIGURE 10 Mean winter concentrations 1968-69 -70

INNER LONDON

Wimbledon

Tottenham

Westminster

Woolwich

River Thames

Dagenham

150
200
150
150
300
300
200
150
150
200

miles
km.

FIGURE 11   MEAN CONCENTRATIONS – JANUARY 1968

INNER LONDON

Wimbledon

Tottenham

Woolwich

Dagenham

River Thames

200 250 300

250

200

200

200

250

200

200

300

250

400

500

200

FIGURE 12

CONCENTRATION-
DIRECTION ROSE
for
Kelvedon Hatch 1969
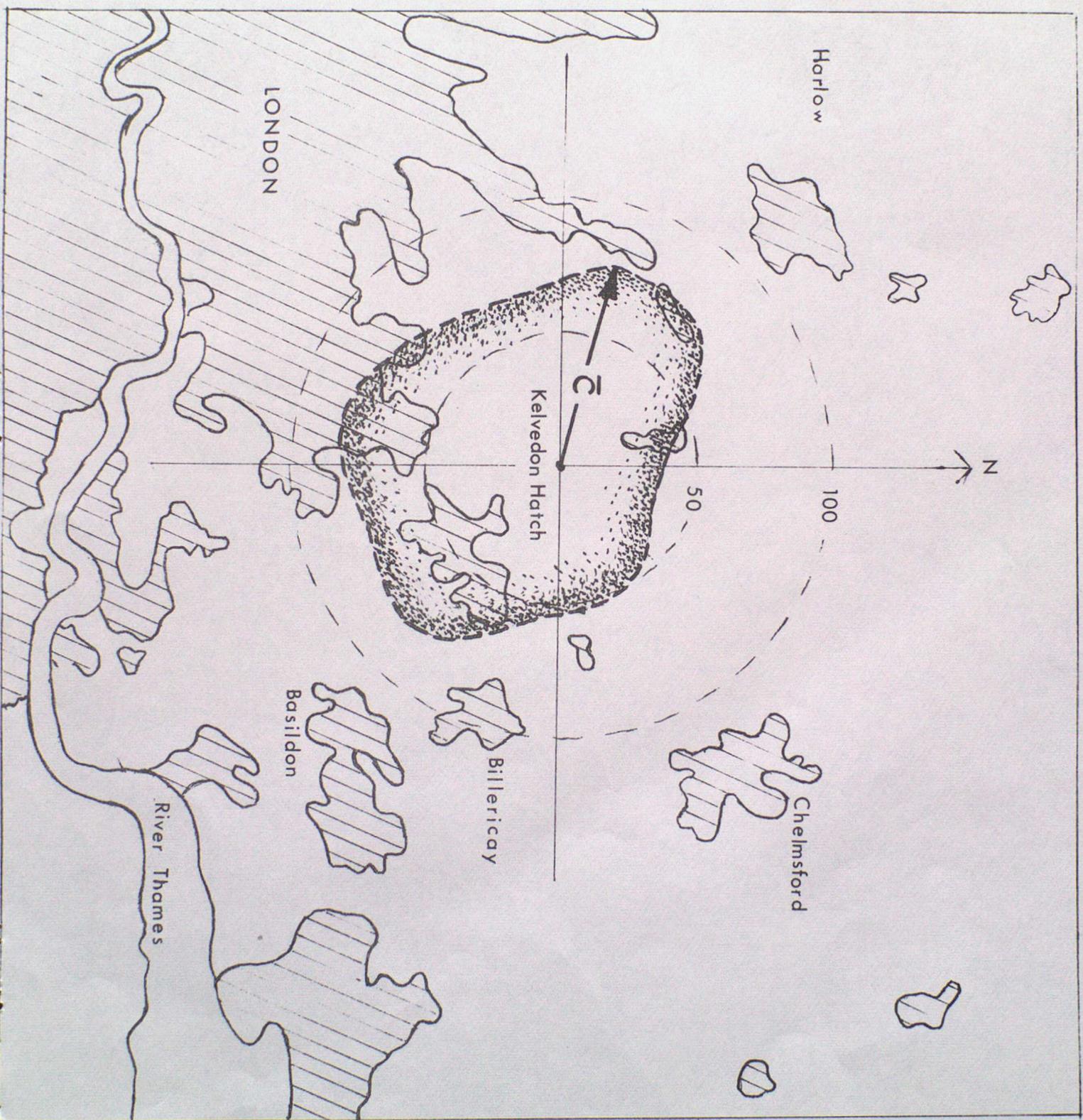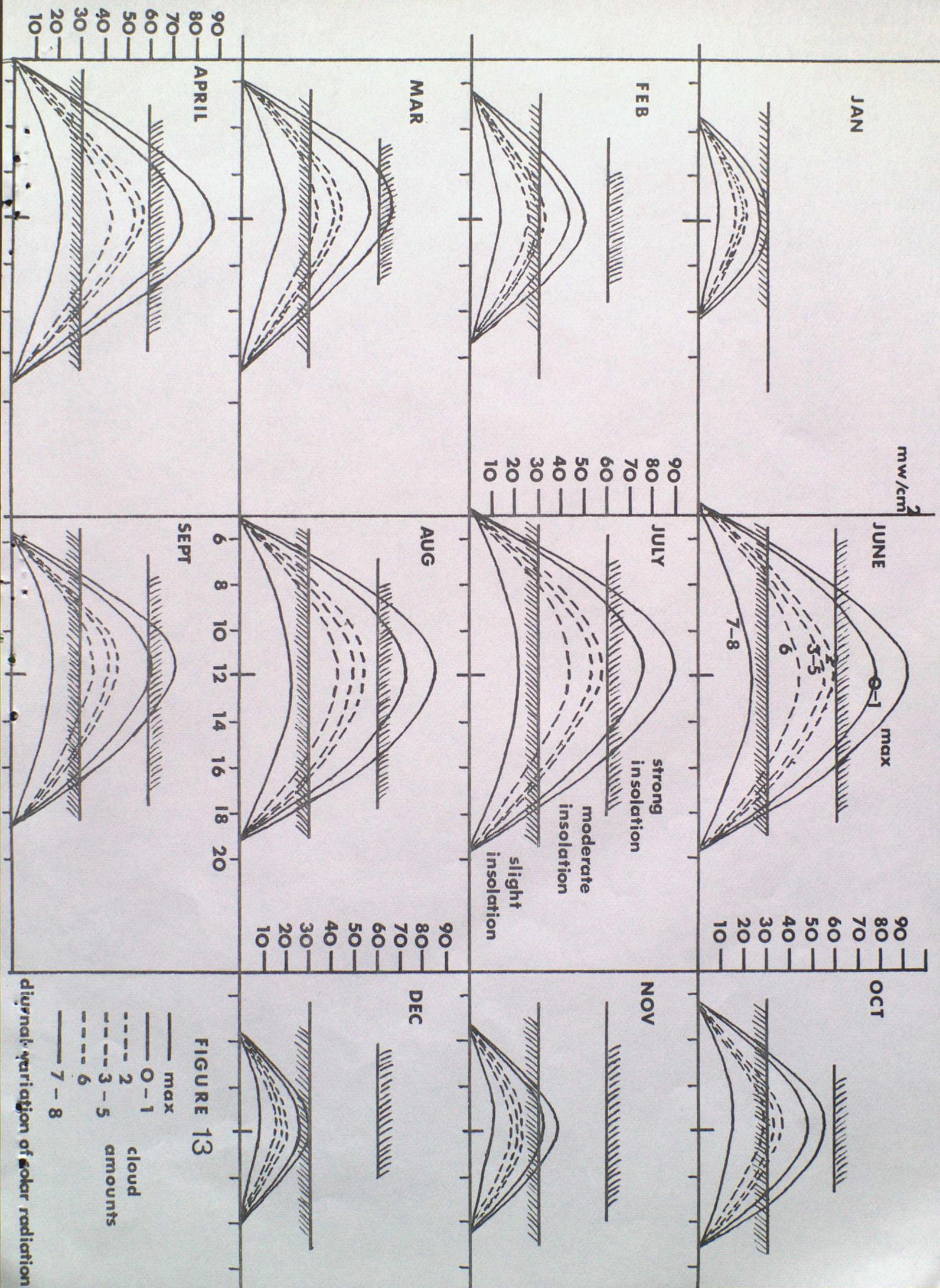
FIGURE 13

diurnal variation of solar radiation

		cloud amounts
——	max	
——	0-1	
- - - -	2	
– – –	3-5	
– – –	6	
——	7-8	

mw/cm²

JAN FEB MAR APRIL

JUNE JULY AUG SEPT

OCT NOV DEC

strong insolation
moderate insolation
slight insolation
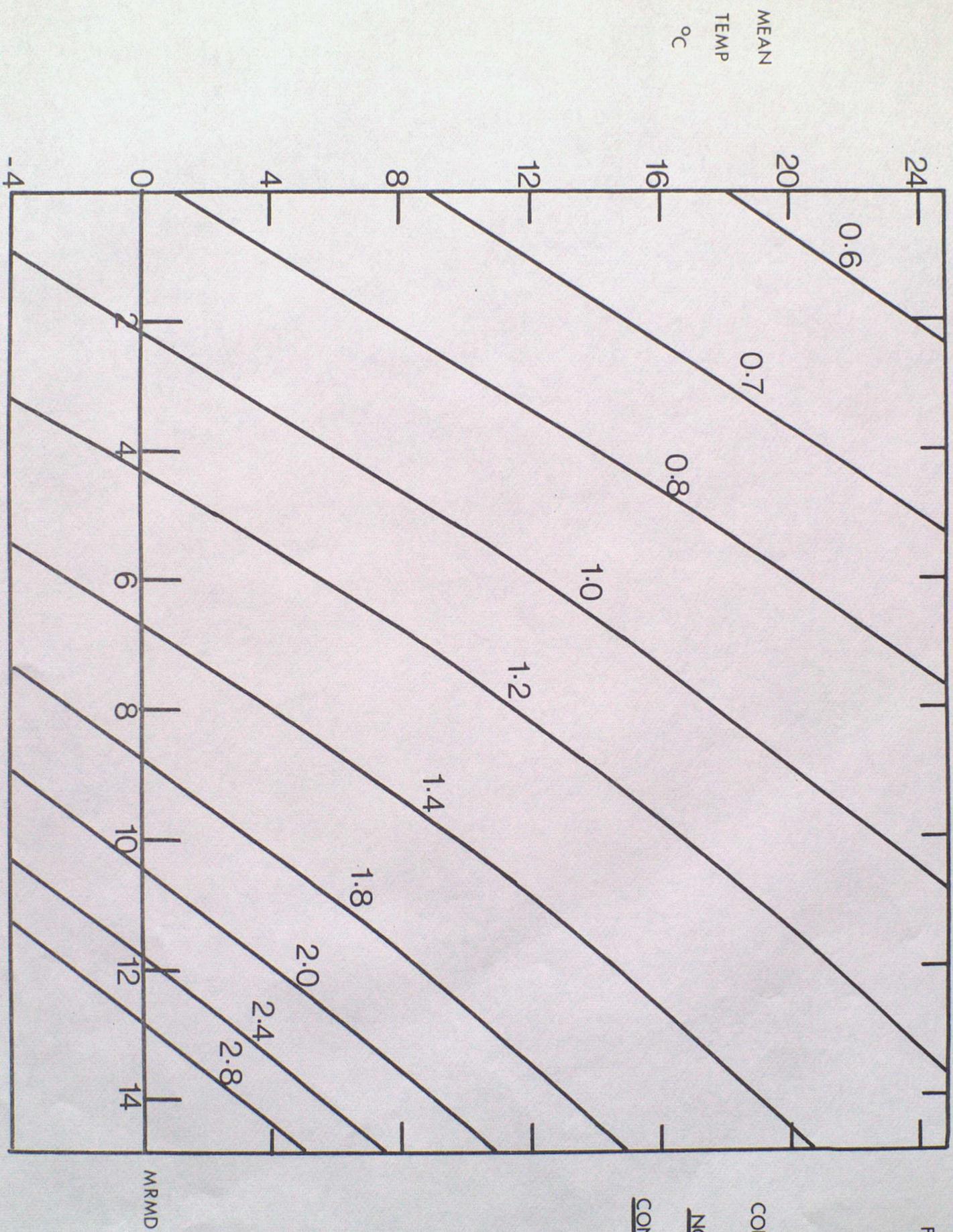
FIGURE 14

CONTOURS OF
NORMALISED
CONCENTRATION

Figure 15

Nomogram for predicting SO₂ concentrations at the four sites in Inner London.
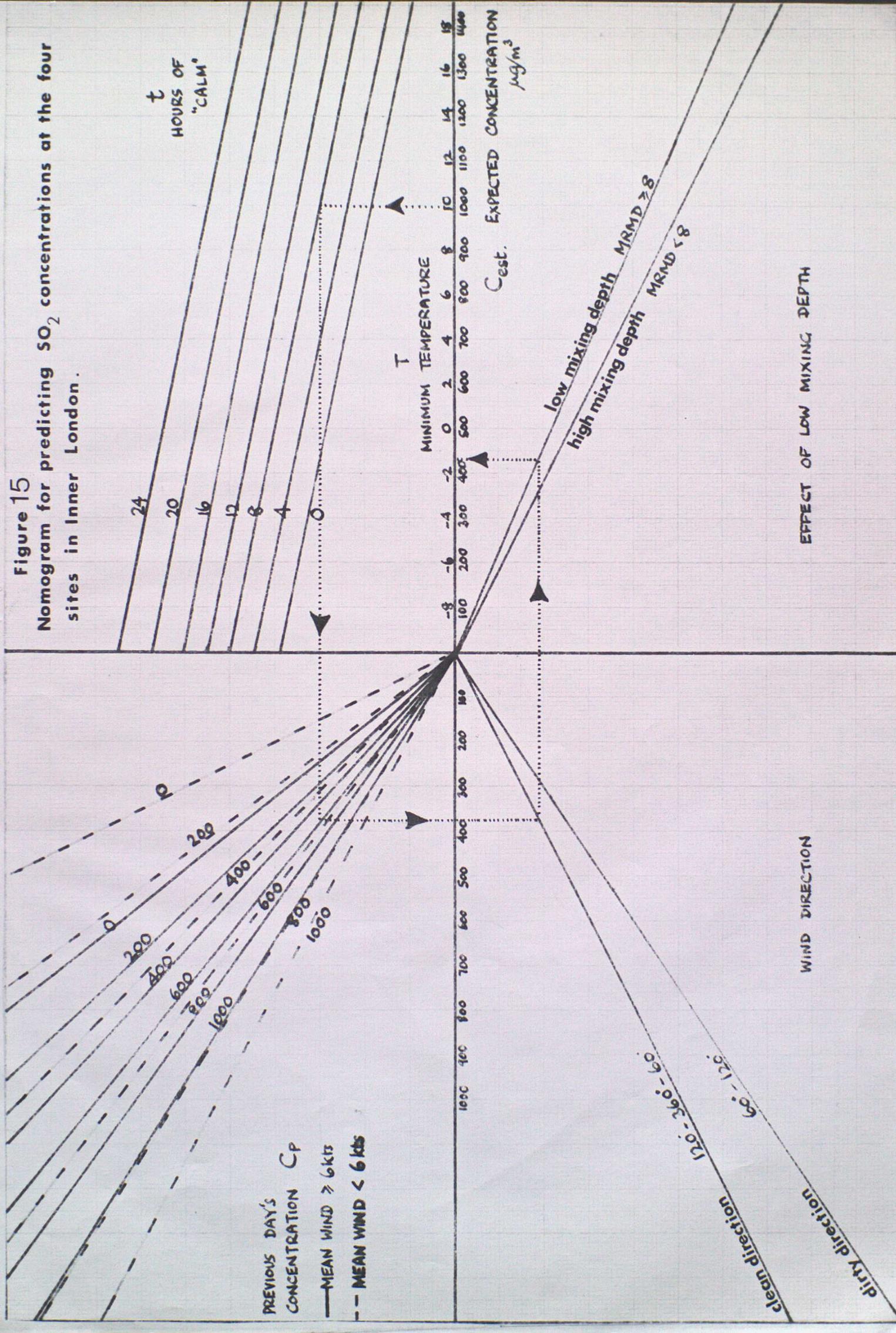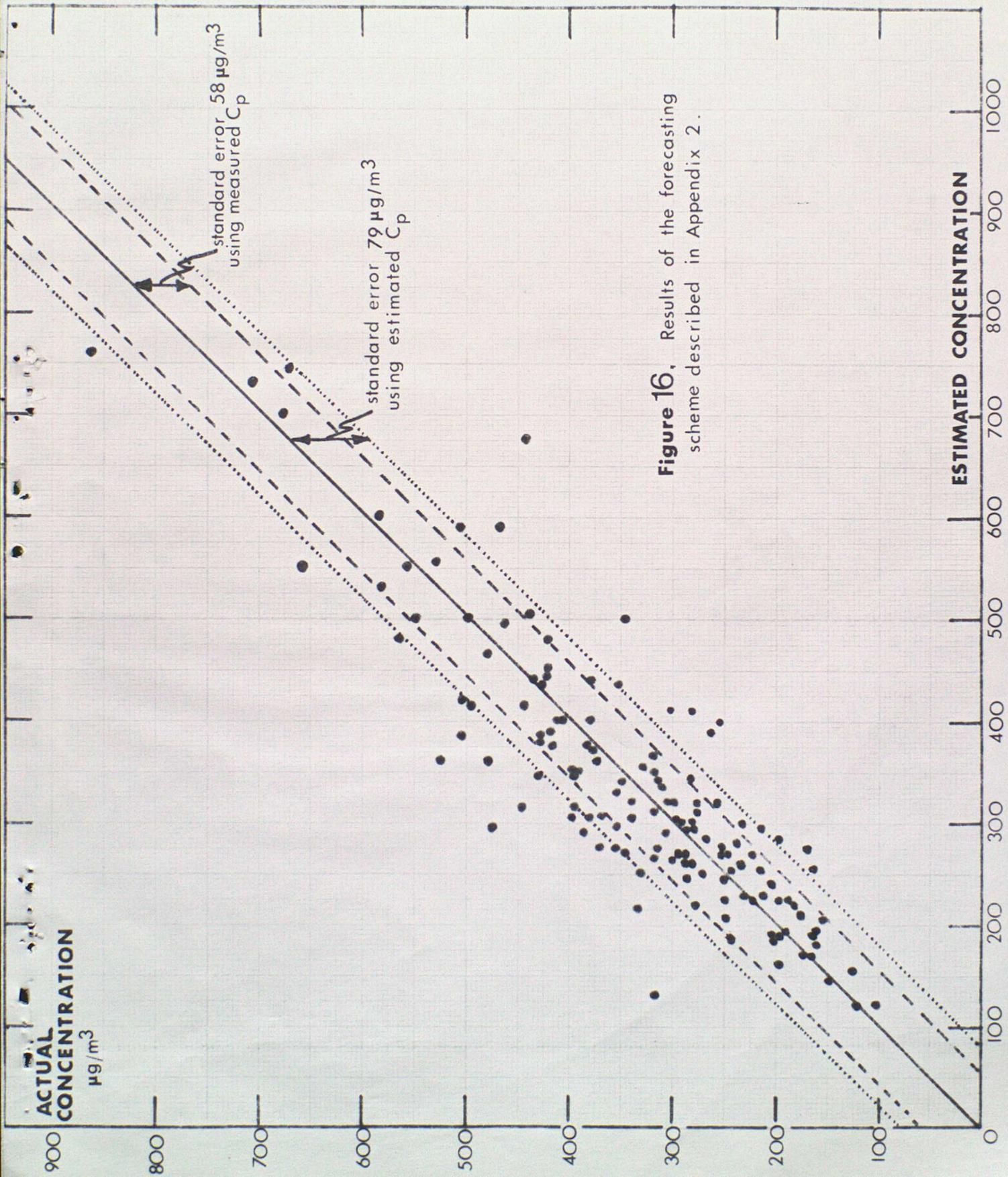
Figure 16. Results of the forecasting scheme described in Appendix 2.

standard error 58 μg/m³ using measured C_p

standard error 79 μg/m³ using estimated C_p

ACTUAL CONCENTRATION μg/m³

ESTIMATED CONCENTRATION