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THE ACCURACY OF FORECASTING POLLUTION

by

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Introduction

Airborne pollutants are worthy of study because of their effects on health, amenity, buildings, animals or vegetation. Sometimes it is the concentration in the air that is important, and how this concentration varies in time. In other cases it is the actual amount of the pollutant which gets deposited per unit surface area of the underlying ground by one means or another. With some pollutants both are important.

In every case the nature of the atmosphere and its ability to carry the pollutant, to dilute it and disperse it, is of vital concern.

To take an example, domestic central heating systems may emit sulphur dioxide, one of the commonest of all air pollutants. The householders will adjust the system to maintain a comfortable temperature inside the home against heat losses caused by conduction and ventilation losses. The rate of emission will therefore probably depend on the exterior wind speed and air temperature.

The 'plume' coming out of the chimney or vent will be warm and will rise. In light winds the rise may be many metres. In stronger gusty winds, the plume will get bent over quickly and may get caught up in the turbulent eddies in the lee of the house and brought down to ground very rapidly. In partial compensation the emission is injected into a longer run of wind in strong winds than in light winds, tending towards overall lower concentrations.

The sulphur dioxide is carried away downwind and the areas affected clearly depend principally on wind direction. At very short range wind direction may be treated as spatially constant. At somewhat longer range allowance might have to be made of the effect on the airflow of such things as the urban heat-island, hills and valleys. Coastal effects (e.g. sea breezes) and large clouds which generate their own meso-scale circulations.

Some of the sulphur dioxide will be absorbed by the ground and the vegetation. Some of the remainder will be oxidised to sulphate and the rate at which this occurs depends principally on the relative humidity of the air, although other meteorological factors may be important. Sulphate is absorbed by the surface much more slowly and can often travel through the atmosphere many hundreds of kilometres. Much of the sulphate is only removed when it is drawn into a rain area and washed out, perhaps at great distances from its original source.

One can see from this briefly considered example, the daunting range of meteorological and environmental parameters that may be important.

Except in very complex cases, the ground-level concentration of a pollutant sampled in the plume over a few minutes and at downwind distances of up to a few kilometres can usually be estimated to within a factor of about 2, compared with actual measured values, provided the emission rate is known. The accuracy improves as the period over which the plume is sampled is increased. The cause of these errors is not principally due to the inadequacies of the models we use, although of course these play some part, but is largely due to the inherent variability within an otherwise uniform air flow. At large distances downwind the accuracy becomes gradually less. The reason for this is that errors in trajectories are typically cumulative, especially on the scale of weather systems, like depressions and anticyclones.

In certain rather important instances it may be essential, or maybe just simply desirable, to forecast concentration levels ahead of time. The following examples illustrate this point. The first example refers to certain cities round the world where concentration levels of smoke and sulphur dioxide occasionally reach such levels as to present a definite hazard to inhabitants with chest and heart complaints. A concentration forecasting scheme then becomes highly desirable in order to advise the public of forthcoming levels, to provide a basis for possible emission control and to prepare hospitals for possible influxes of patients.

The second example refers to the accidental release of some toxic, explosive or radioactive material from an industrial plant. Often the release is not instantaneous but is spread over many hours. During this time the wind field (and other meteorological parameters) may change very significantly. In order to dispose whatever emergency services are available to the best possible advantage of the public, some estimate of these changes is required as soon as possible after the accident is appreciated.

The third example concerns the long range transport of industrial air pollutants and the depositions experienced in sensitive areas, maybe one or more thousand kilometres from the source regions. The deterioration in the fauna-supporting quality of many Scandinavian lakes is an example of this situation. Acid rain appears to be a major contributing factor to the decline in lake pH values and a consequential decline in the fish populations there. In theory it would be possible to alleviate this problem by forecasting air movements to Scandinavia two or three days in advance and applying fuel switching to more expensive low-sulphur fuels at appropriate large industrial plants where this would be feasible. In practice this is a costly solution and in any case such forecasting is obviously subject to error.

The object of this paper is to look at some of these forecasting situations and to attempt to assess the accuracy with which the relevant meteorological parameters can be forecast and the consequences this has on the accuracy of concentration predictions.

Let us briefly summarise the situation here. Detailed figures will be given in the full paper.

1. URBAN POLLUTION

The Meteorological Office sulphur dioxide forecasting model for London has been in operation during the winter months since 1971, and provides a useful guide to trends in concentration. Twenty four hour average concentrations are forecast each day for the following day. Correlations between predicted and actual concentrations are typically about 0.7 to 0.75. The errors in forecasting the meteorological parameters, although relatively small, nevertheless are one of the principal sources of error in the model. Two of these parameters are the expected minimum temperature (root mean square (r.m.s.) error $2^{o}C$) and the number of hours when the mean wind falls below 5 knots (r.m.s. error 4 hours). In combination these result in a r.m.s. error of concentration of about 50 $\mu g\ m^{-3}$ (compared with a winter mean SO_2 concentration of about 200 $\mu g\ m^{-3}$).

Wind direction is relatively unimportant in most cities unless one or two very strong sources dominate the concentration pattern.

2. ACCIDENTAL RELEASES OF HAZARDOUS POLLUTANTS

The principal error here arised from changes in wind direction. An analysis of time sequencies of trajectories over a range 1 to 30 km have been analysed based on hourly surface wind observations. These variations were compared with corresponding changes in geostrophic wind direction deduced from the normal synoptic network of observing stations.

Other errors arise from variations in atmospheric stability, especially in the lower layers, and in wind speed. More serious accidents might potentially affect areas out to some 1000 km or more. A study of "trajectory swinging" in time out to these ranges have been analysed and the results include the effects of release period on the magnitude of the swinging.

3. EMISSION CONTROL IN THE LONG RANGE TRANSPORT OF POLLUTION PROBLEM

An analysis has been made of comparative trajectories based on forecast and actual meteorological charts over distances of the order of 1000 km (roughly the distance from London to southern Norway). It shows that the root-mean-square error at this range is of the order of 250 km which is roughly the width of Norway as viewed from southern England. Consequently fuel changing based on such forecasts could result in many failures, either misses when a hit was forecast, or vice versa. The quality of forecasting several days ahead is nevertheless improving and it may ultimately become more feasible than it is at present.

Stability of the atmosphere and dispersion

Vertical diffusion of pollutants up or down through the atmosphere is caused by turbulent eddies embedded in the mean airflow. The more intense these eddies are, and the larger they are, the more rapid is the dispersion. If we have rapid dispersion then for sources that are some height above the ground, the concentration of whatever is being emitted is at first enhanced at the ground but is later diminished. For ground level sources, the surface concentrations are always reduced by rapid vertical dispersion.

There are two sources of energy for these turbulent eddies. As Figure 1 shows the first arises from the braking action of a rough underlying surface on the airflow. Energy is transferred from the mean motion to the eddies. These eddies in turn help to bring down mean-motion momentum from aloft to balance the losses in the surface layers. The intensity of turbulence increases both with wind speed and with roughness of the underlying surface. The typical vertical eddy velocity is about one-eighth of the wind speed measured at 10 metres over normal countryside.

The second major source (or sink) of turbulent energy is the buoyancy generated by internal density or temperature differences. These differences arise from the air and the underlying ground surface having different temperatures and water vapour pressures. Over land we can usually ignore the latter and think only of the consequential flux of sensible heat either from the ground into the air (when the ground is hotter than the air as it often is in the dat) or the reverse (as often happens at night).

As shown in Figure 2, incoming solar radiation during the day tends to heat the ground and some fraction of this may enter the overlying air as sensible heat. The elevation of the sun, the amount and type of cloud and the dampness and character of the ground surface are obvious factors determining the upward heat flux. At night the ground usually cools as outgoing long-wave radiation exceeds incoming radiation originating mainly from any clouds present.

When the sensible heat flux is upwards (from the ground to the air) the air temperature tends to increase rapidly downwards, and in consequence any fluid element perturbed upwards, say, soon finds itself hotter than its environment and gravity accelerates it upwards. The motion is unstable, turbulent notions tend to be intense and chimney plumes disperse rapidly and are sometimes fragmented (see Figure 3). At night when the heat flux is downwards, the temperature decreases donwwards and perturbed fluid elements are soon restored back to their original levels. Turbulence may be entirely quenched in time, especially in clear sky conditions when surface cooling is rapid and in light winds when the dynamic generation is small.

In 1959 Pasquill, recognising these physical principles, tried to relate what experimental data on vertical dispersion was available at that time to meteorological factors related to these basic parameters. It was clearly sensible to select factors which could be rapidly observed or assessed without sophisticated instrumentation. The scheme developed was in this sense based soundly on good physical and practical concepts, but the details of the relationships were empirical. Only now are the forms of these relationships being verified by theoretical arguments. Pasquill defined six stability categories, A to F, in which A represents the most unstable conditions, B and C less unstable, D neutral, E and F stable conditions. Later a very stable category G was added to the list. Smith's modified form of Pasquill's scheme for the unstable categories is shown in Figure 4. The sensible heat flux can be estimated roughly by a variety of methods. Figure 5 shows typical values. A somewhat better method is to deduce the current elevation of the sun and, allowing for the amount of cloud, deduce the net incoming solar radiation R. An estimate of the sensible heat flux H can then be found by using the equation

$$H = 0.4(R - 100)$$

where H and R are in watts per square metre. Full details of this method are given in Pasquill's famous book "Atmospheric Diffusion" (2nd Edition). Even better practical methods are available but would take too long to describe here.

Knowledge of the Pasquill stability P, the wind speed u and the roughness of the ground enable unique estimates of plume depth to be determined as a function of distance downwind from the source. The following sections will be devoted to considering the errors in estimating the wind and the Pasquill stability and what effect this has on ground level concentrations downwind from a large elevated source (like a power station chimney).

<u>The Problem of estimating the wind</u>

Errors almost always exist in estimates of wind speed and direction. If you are concerned with whether or not you are being affected by the plume then wind direction is of prime importance - either you are in the plume or the wind direction is carrying the plume to one side. On the other hand wind speed is important if you are concerned with maximum ground level concentrations, whereever thay may occur. Wind speed, as we have seen, affects the stability P as well as the dilution of the plume at source and the amount of plume-rise that occurs with buoyant plumes.

Most meteorological stations are equipped with wind vanes and anemometers which obviously must be of robust and long-lasting quality. The penalty for this robustness is that they are not highly sensitive (unlike research instruments) and in low wind speeds tend to be decidedly inaccurate. This is particularly significant for the estimation of the extreme P categories, A and G, which only exist with low wind speeds. At very low speeds the instruments do not even respond and at somewhat higher speeds the accuracy can be rather low. For example the so-called starting speeds for a wind vane are typically of the order 1 to 1.5 ms^{-1} whereas for an anemometer they are 3 - 4 ms^{-1}. A good meteorological observer will however apply his own judgement when making his readings and a likely final error in wind speed, below about 6 ms^{-1}, is only about 1 - 2 ms^{-1}. (Bad enough, you may say!).

The next problem is that the met. station is not directly beside your chimney but may be up to 50 or 60 kilometres away. Obviously winds do vary across the country in both speed and direction. C.G.Smith has recently done an analysis of the correlation between winds measured at neighbouring met. stations in three areas of the United Kingdom. All the areas are lowland areas. They are the lowland area of central Scotland (which is subject to some topographical effects), south east England and, thirdly, East Anglia (when topographical effects are probably at a minimum). Figure 6 shows an interpretation of his results in terms of likely errors in speed and direction as a function of distance from the meteorological station. For example if this distance were 30km then errors of 1.35 ms^{-1} and 29^0 would be typical in the Scottish lowlands area. This assumes that your site is as well exposed as the typical meteorological station. If it isn't, then some further correction is necessary. If the effective local surface roughness can be estimated, a shot at this can be made, but is almost bound to be subject to error of at least 1 ms^{-1}.

This extrapolation from a neighbouring met. station can be particularly suspect if your site is subject to the influence of some marked local topography - a mountain, a valley, a city or a coastline. All these features tend to distort the airflow. An example of this is illustrated by the convoluted trajectories determined by Dr. Carpenter's rather sophisticated numerical meso-scale model for a warm June day when sea-breeze circulations were very evident. No further comment is required, I think, to emphasise the difficulties these effects pose.

So far we have considered only the problem of estimating winds at 10 metres in real time. Two further problems have to be considered. Firstly given the 10 metre wind, how do we find the wind at stack height? Smith and Carson (1974) have considered average relationships during the day, but at any one time, day or night, these can only provide a very rough guide. Errors of at least 2 ms^{-1} could be readily foreseen in this extrapolation, although at present I have no actual data to support this estimate.

The second problem arises if we wish to forecast the wind field ahead of time as we might for example if we were responsible for directing emergency procedures and services at the beginning of an accidental release of some hazardous airborne material from a chemical factory or nuclear power station which might persist over many hours. The obvious action is to consult your local meteorological forecasting office. Certainly their advice about likely trends in wind speed and direction will be invaluable. However it must be recognised they are faced with considerable problems in deciding upon the magnitudes of the changes that are likely to occur. Firstly they do not have a meso-scale model like Carpenter's model operationally available to them to cope with the effects of your local topography, Secondly they are bound to rely to some degree on the results of the numerical forecasting model in their predictions. In many respects these models give excellent results, but are generally not too reliable in their forecasts of surface winds. This is because these winds are deduced from the pressure fields at a level about 1 kilometre up in the atmosphere. To relate the two, rather simple empirical rules are employed which must obviously be rather suspect. Figure 8 tabulates some of the errors determined by direct verification tests.

Overall then we can see we would be doing well in an operational situation if we could estimate the wind speed at stack height to within 2 - 3 ms^{-1} and a wind direction to within 30^0 unless we had some mean of directly estimating these, say by visual observations of the plume itself.

Although this section has been concerned with winds, we should end with a quick comment about errors in heat flux (and hence in P). Heat flux can be estimated quite readily to within $\pm 40\ Wm^{-2}$. In unstable conditions this is quite adequate and in conjunction with errors in wind speed is likely to yield typical errors in P of about one class at most. On the stable side the situation is rather harder, the range in H is smaller and perhaps the hardest question to answer is whether or not some vestige of turbulence remains or whether it has been quenched and vertical turbulence is virtually non-existent, which often happens on quiet clear-sky nights.

Estimating Concentrations downwind from a large chimney

Very many studies of power station plumes have been made and almost as many different formulae have been recommended to estimate plume rise and ground level concentrations. I hesitate as a mere meteorologist to enter into this arena, especially since I have made no survey of my own. Consequently I feel compelled to accept the findings of the very thorough study carried out by C.E.R.L. and C.E.G.B. described in the literature in several papers by, amongst other, Dr. D.J.Moore. I will accept their data and their formulae as being the best, or amongst the best available at the present time. Their equations are necessarily rather complex (see for example Moore, (1974), Advances in Geophysics, p.220). It is probably over-bold of me to try to simplify these, but it has been my experience that good estimates can be obtained very quickly using the simplified scheme set out in Figures 9 - 13. It should be stressed that these estimates are based on actual measurements made round real power stations in the U.K.. Figure 9 gives an estimate of the average maximum ground level concentration, $\bar{C}_{max}$ given the output of heat Q_H (in MW) and the stack height h_s (in metres), averaged over all meteorological conditions. Q_H can be estimated if the electrical output of the station is known:

$$Q_H \approx \frac{1}{6} Q_{elect.} \text{ in MW.}$$

We have assumed that typically the output of sulphur dioxide Q (gs^{-1}) is related to Q_H by:

$$Q \approx 25\, Q_H$$

As the equation in the Figure shows this assumption is not necessary if Q is otherwise known.

Figure 10 gives the best estimate of the actual maximum concentration C_{max} in a given (u,P) situation once $\bar{C}_{max}$ is found. The behaviour of the C_{max} contours incorporates the effect of u and P on plume rise, dilution at source and depth of the mixing layer in a direct empirical way through the real data on which it is based.

Figure 11 shows how this maximum concentration varies with sampling time. This allows for the effect of typical wind direction changes due to changes in the synoptic, meso-scale and small scale wind fields, and allows for the finite width of the plume at any instant.

Figures 12 and 13 provide equivalent information x_{max}, the distance downwind in kilometres where the maximum ground level concentration is expected to occur.

Figure 14 illustrates the downwind distribution of concentration relative to C_{max} and x_{max}.

Overall this scheme provides a quick and reasonably accurate means of estimating the concentration field based on Moore's more detailed analysis of this problem.

Errors in estimating C_{max} and x_{max}

As we have already seen one major source of error is likely to arise from uncertainties in the wind speed u at stack height and in the Pasquill Stability P. Figure 15 uses our estimates of these errors in conjunction with the scheme for estimating C_{max} and x_{max} just outlined to estimate likely errors in C_{max} and x_{max}. Most of the errors are acceptable although errors in C_{max} in stable conditions are, as one might expect, rather large.

Figures 16 and 17 show that in practice there are other causes of error which are not explained solely by errors in u and P. These arise from a variety of causes. One major cause is that emissions from chimneys are difficult to estimate accurately (due to variability in sulphur content of the fuels and variability in time in fuel useage).

Another source of error which on many occasions must be very important is variability in the internal structure of the boundary layer. This structure arises in an evolutionary sense during the upwind passage of the airmass over terrain with complex time-varying thermal properties and roughness. In particular, inversion heights and strength are quite variable especially at night. If it was expedient to do so, some valuable information on the nature of these inversions can be obtained from data collected during routine radiosonde ascents at one of the few radiosonde stations round the U.K..

Another variable phenomena, more typical of daytime conditions, is illustrated in Figure 18. Large Ekman-type rolls orientated with their axes more or less parallel to the wind, can fill the boundary layer. The circulation associated with these rolls can draw in a plume and carry it upwards and spread it out at the base of the capping inversion. Such behaviour is bound to considerably affect ground level concentrations.

The final cause of error which will be referred to is concerned with the effect of wind direction changes. Some measure of the synoptic component of these changes is shown in Figure 19. The angular spread caused by changes in the synoptic meteorological field is of necessity a function of the time over which the plume is sampled. Geostrophic wind directions have been sampled over a two year period and analysed in terms of sampling time T. Figure 19 shows that for T = 1 hour, say, the average swing in the wind is 2^0 but on 10% of occasions the swing exceeds 8.5^0. For 10 hours, the mean is 20^0 but 10% lie above 80^0 and 10% below 5^0. Some correlation must exist with wind speed and synoptic situation but this is a subject for future research. Nevertheless it is clear this can be an important source of variability in C_{max} for given Q_H, h_s, u and P.

Overall then it is not surprising that estimating C_{max} and x_{max} is a formidable problem. Over flat terrain estimates of C_{max} within a factor of 2 (for t = 1 hour) are as much as we can hope to achieve.

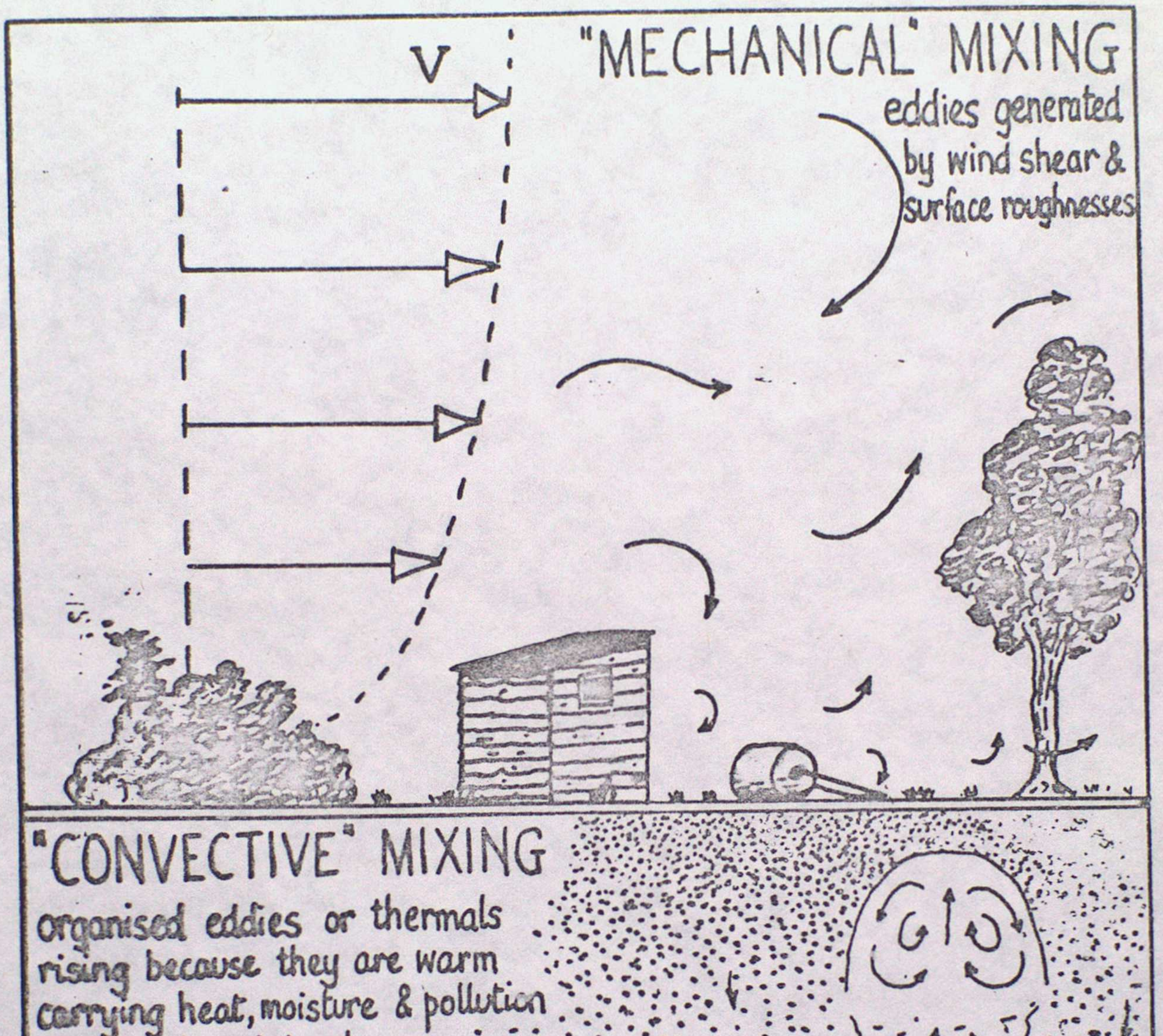

V
"MECHANICAL" MIXING
eddies generated by wind shear & surface roughnesses
"CONVECTIVE" MIXING
organised eddies or thermals rising because they are warm carrying heat, moisture & pollution through the mixing layer.

FIGURE 1.

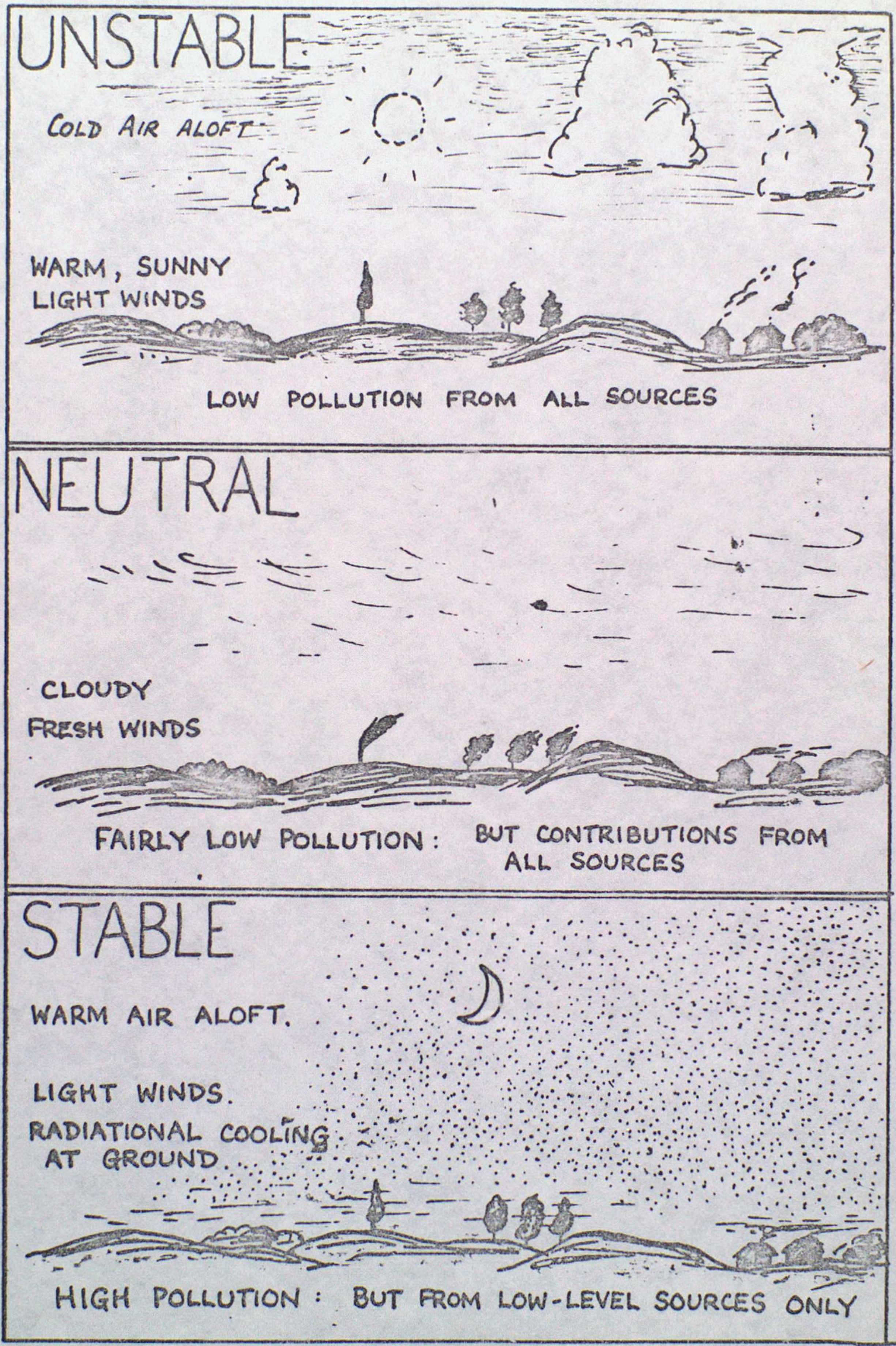

UNSTABLE
COLD AIR ALOFT
WARM, SUNNY
LIGHT WINDS
LOW POLLUTION FROM ALL SOURCES
NEUTRAL
CLOUDY
FRESH WINDS
FAIRLY LOW POLLUTION: BUT CONTRIBUTIONS FROM ALL SOURCES
STABLE
WARM AIR ALOFT.
LIGHT WINDS.
RADIATIONAL COOLING AT GROUND.
HIGH POLLUTION: BUT FROM LOW-LEVEL SOURCES ONLY

FIG. 2.

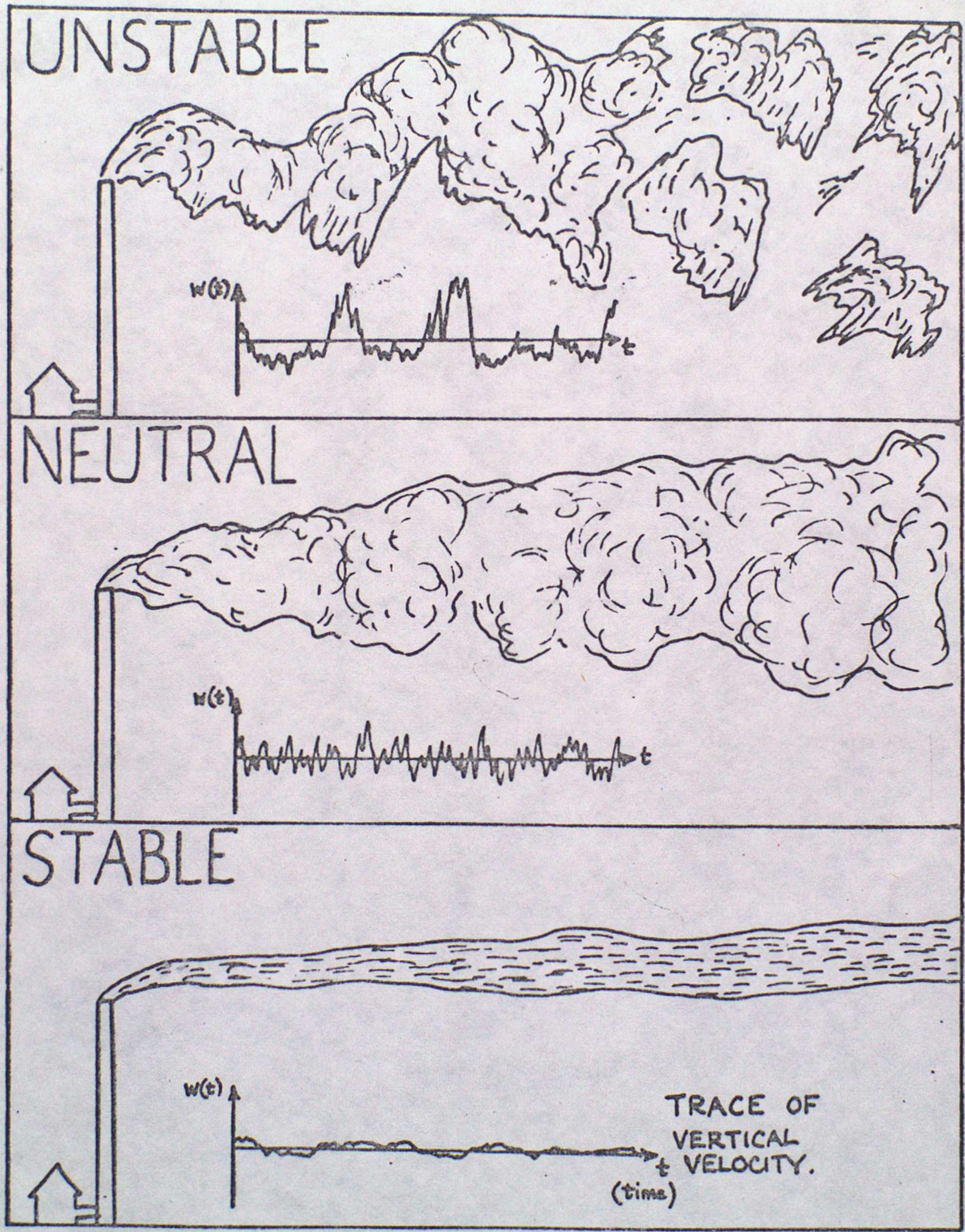

UNSTABLE
w(t)
t
NEUTRAL
w(t)
t
STABLE
w(t)
TRACE OF VERTICAL VELOCITY.
t
(time)

FIG. 3.

FIGURE 4. The revised scheme for P based on lines of constant μ.

$z_0 = 0 \cdot 1m.$

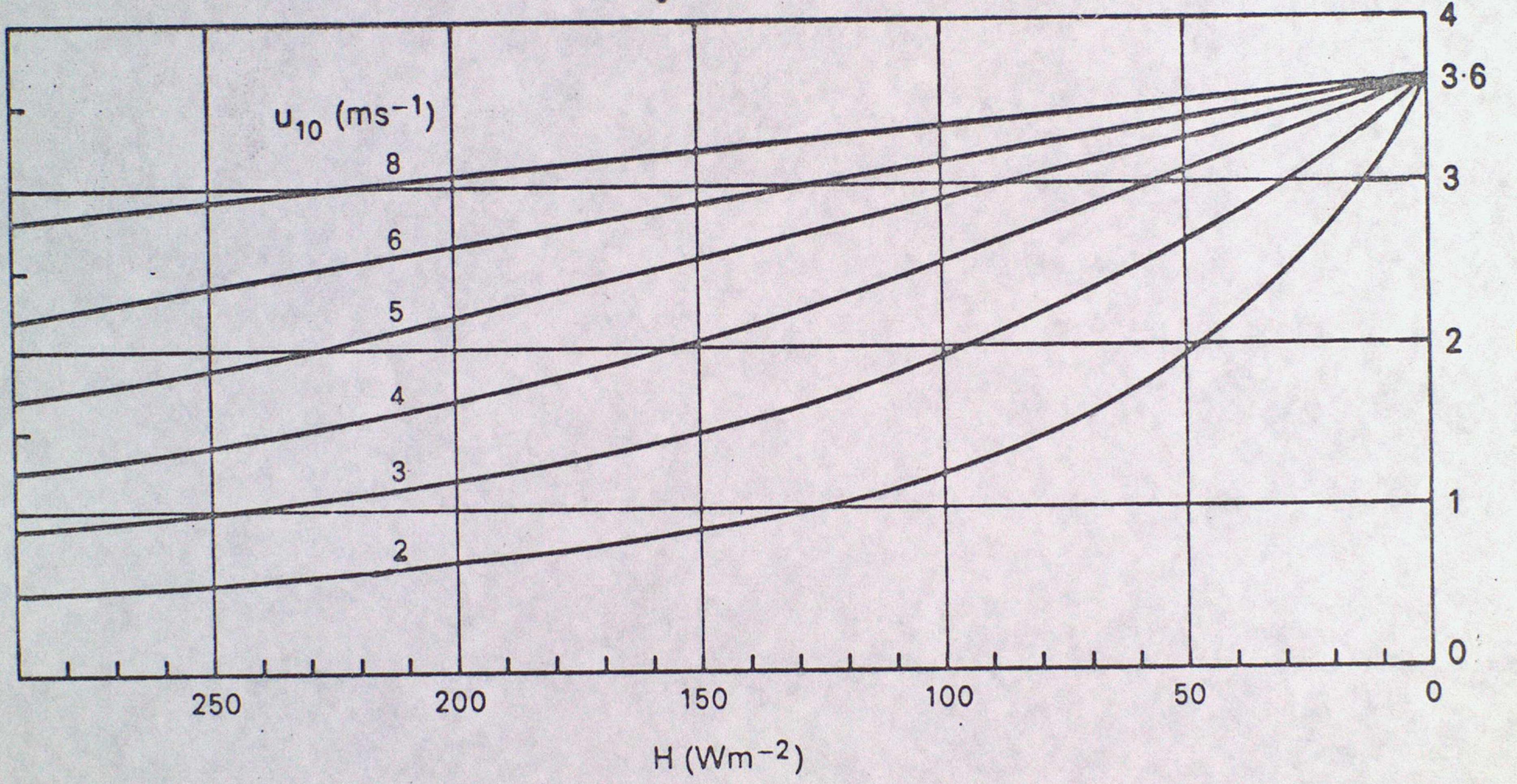


FIG. 4.

SURFACE SENSIBLE HEAT FLUX

H (watts/m^2)

Typical values: (at midday)

Winter's day: −20 very cold ground

nice winters day +50 Wm^{-2}

Spring: cloudy: 40 Wm^{-2}

clear skies: 200 Wm^{-2}

Summer: cloudy: 80 Wm^{-2}

clear skies: 300 Wm^{-2}

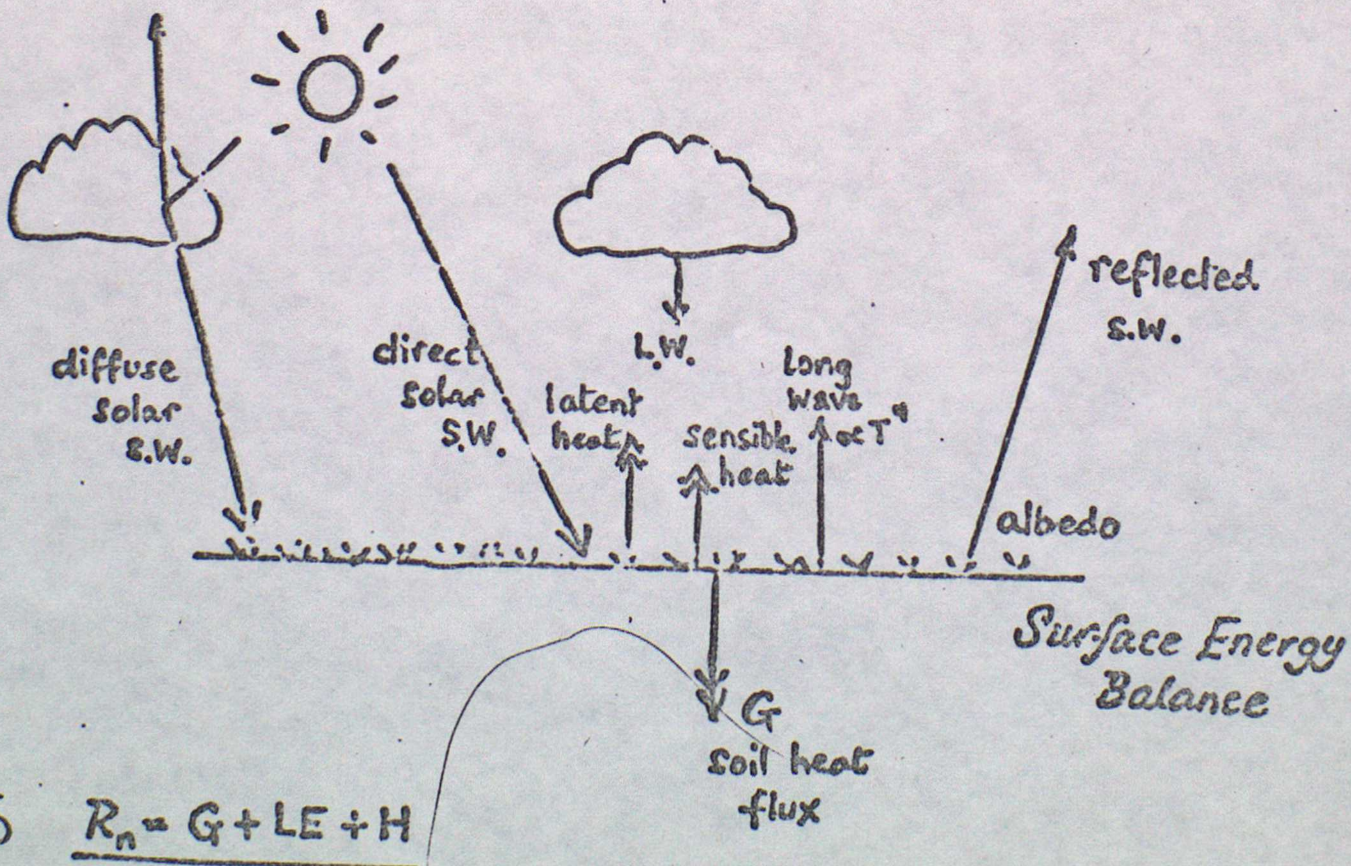


FIG. 5 $R_n = G + LE + H$

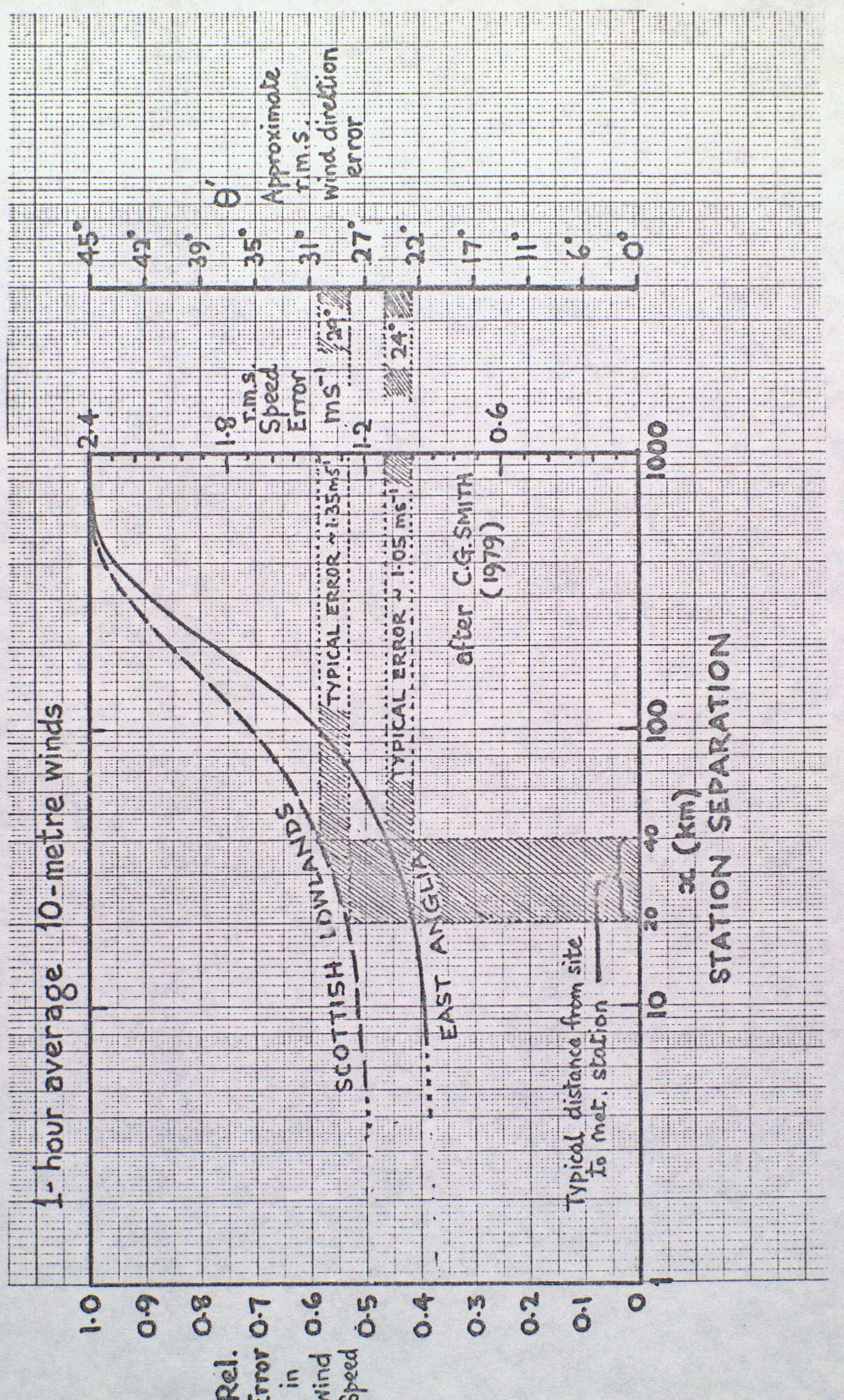

1-hour average 10-metre winds
Rel. Error in Wind Speed
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
SCOTTISH LOWLANDS
EAST ANGLIA
TYPICAL ERROR ~ 1·35 ms⁻¹
TYPICAL ERROR ~ 1·05 ms⁻¹
after C.G. SMITH (1979)
Typical distance from site to met. station
10
20
40
100
1000
x (km)
STATION SEPARATION
r.m.s. Speed Error ms⁻¹
2.4
1.8
1.2
0.6
29°
24°
θ'
Approximate r.m.s. wind direction error
45°
42°
39°
35°
31°
27°
22°
17°
11°
6°
0°

Figure 6.

TRAJECTORY INITIAL DATA TIME = 4Z 14/6/73

PARTICLE HEIGHTS SHOWN EVERY 2 HRS. (24 HR PERIOD) DT=10 MINS

K. CARPENTER'S NON-HYDROSTATIC MESO-SCALE MODEL WITH TOPOGRAPHY

NOTE STRONG SEA-BREEZE ACTIVITY

FIG. 20

[Release time 04Z. Marks every 2 hours
Run for 24 hours]

Figure 7.

NUMERICAL 10-LEVEL OPERATIONAL FORECASTING MODEL

ERRORS IN WIND FORECASTS

OVER LAND : no data available.

OVER NORTH SEA: 10 metre winds :

up to 24 hrs ahead { speed errors : ~ $2.5\ ms^{-1}$
direction errors : $15° - 30°$

OVER NORTH ATLANTIC : wind direction errors :

Verification against ocean weather ship observations :

	Forecast error	Persistence error
T+0	25°	–
T+12	37°	50°
T+24	41°	65°
T+36	48°	70°

Verification against mobile ship observations :

	Forecast error	Persistence error
T+0	39°	–
T+12	41°	58°
T+24	44°	74°
T+36	48°	82°

Figure 8.

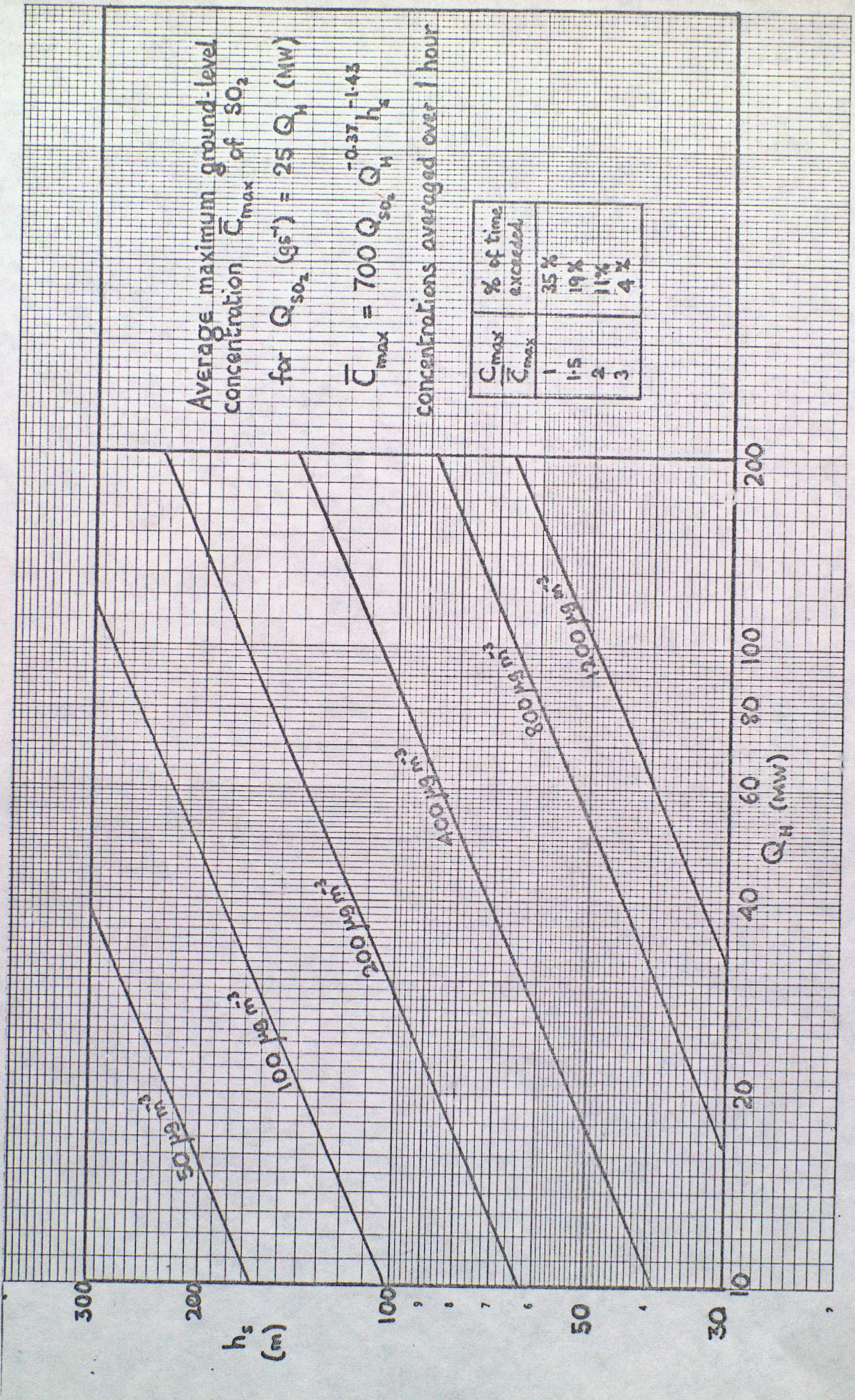
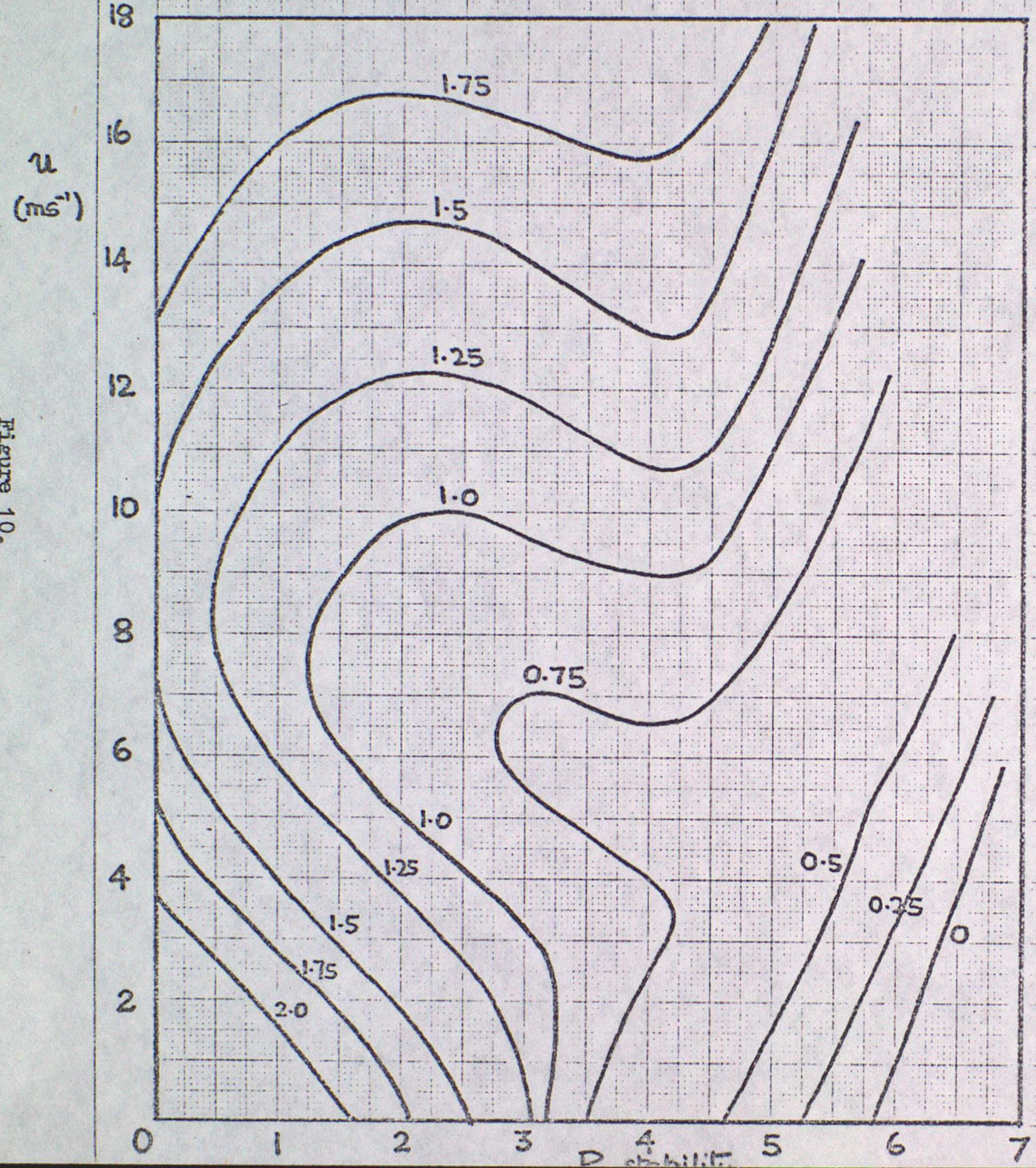

Average maximum ground-level concentration $\bar{C}_{max}$ of SO_2
for Q_{SO_2} (gs^{-1}) = 25 Q_H (MW)
$\bar{C}_{max} = 700\, Q_{SO_2}\, Q_H^{-0.37}\, h_s^{-1.43}$
concentrations averaged over 1 hour
$C_{max}/\bar{C}_{max}$ | % of time exceeded
1 | 35 %
1·5 | 19 %
2 | 11 %
3 | 4 %
50 μg m^{-3}
100 μg m^{-3}
200 μg m^{-3}
400 μg m^{-3}
800 μg m^{-3}
1200 μg m^{-3}
h_s (m)
300
200
100
50
30
10
20
40
60
80
100
200
Q_H (MW)

Figure 9.



CONTOURS OF

$$\frac{C_{max}}{\overline{C}_{max}}$$

where :

$$\overline{C}_{max} \approx 700\, Q_{SO_2}\, Q_H^{-0.37}\, h_s^{-1.43}$$

in $\mu g\, m^{-3}$

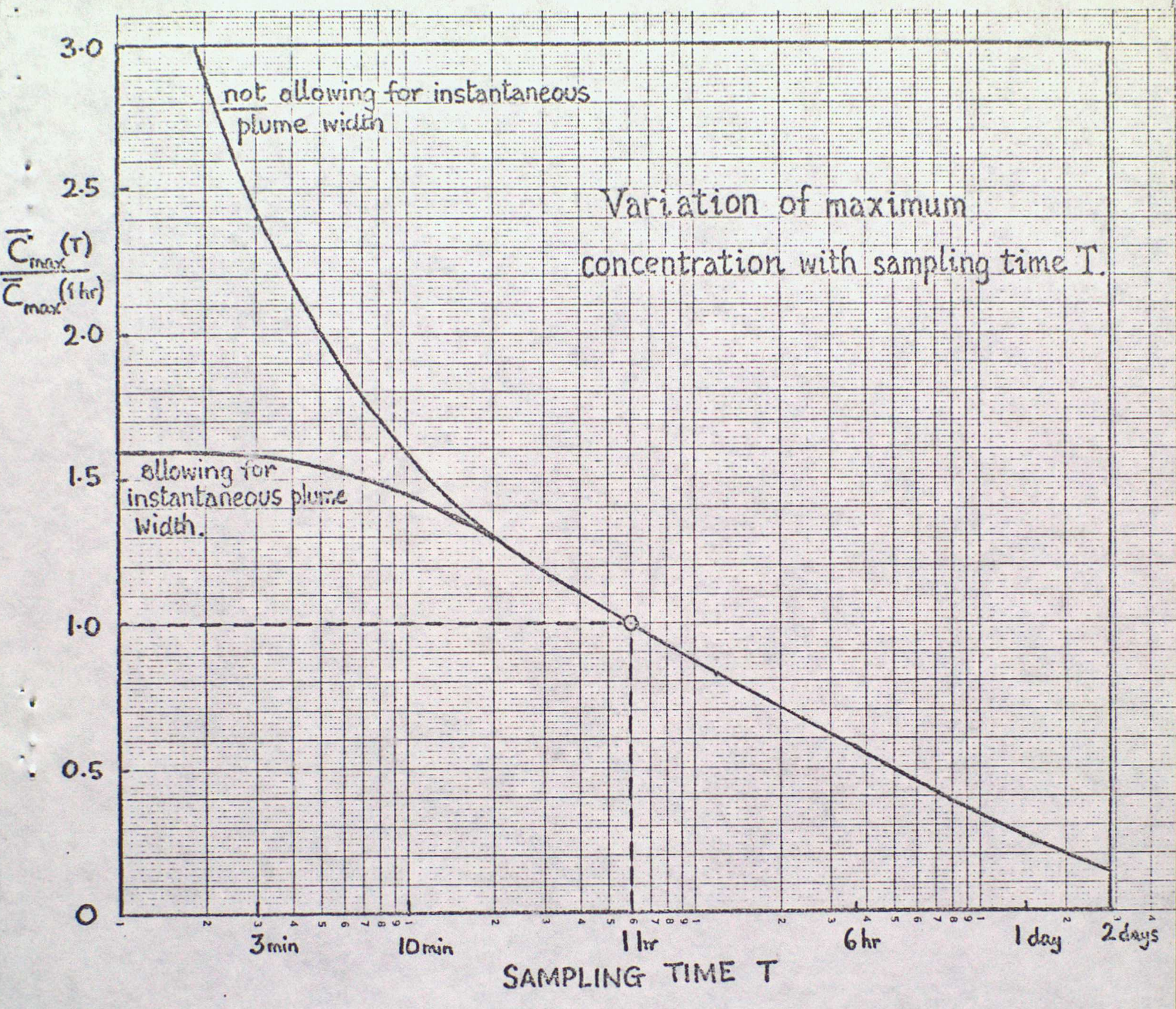
and Q_{SO_2} is in $g s^{-1}$ (output of SO_2)

Q_H is in MW (output of heat)

h_s is in metres (stack height)

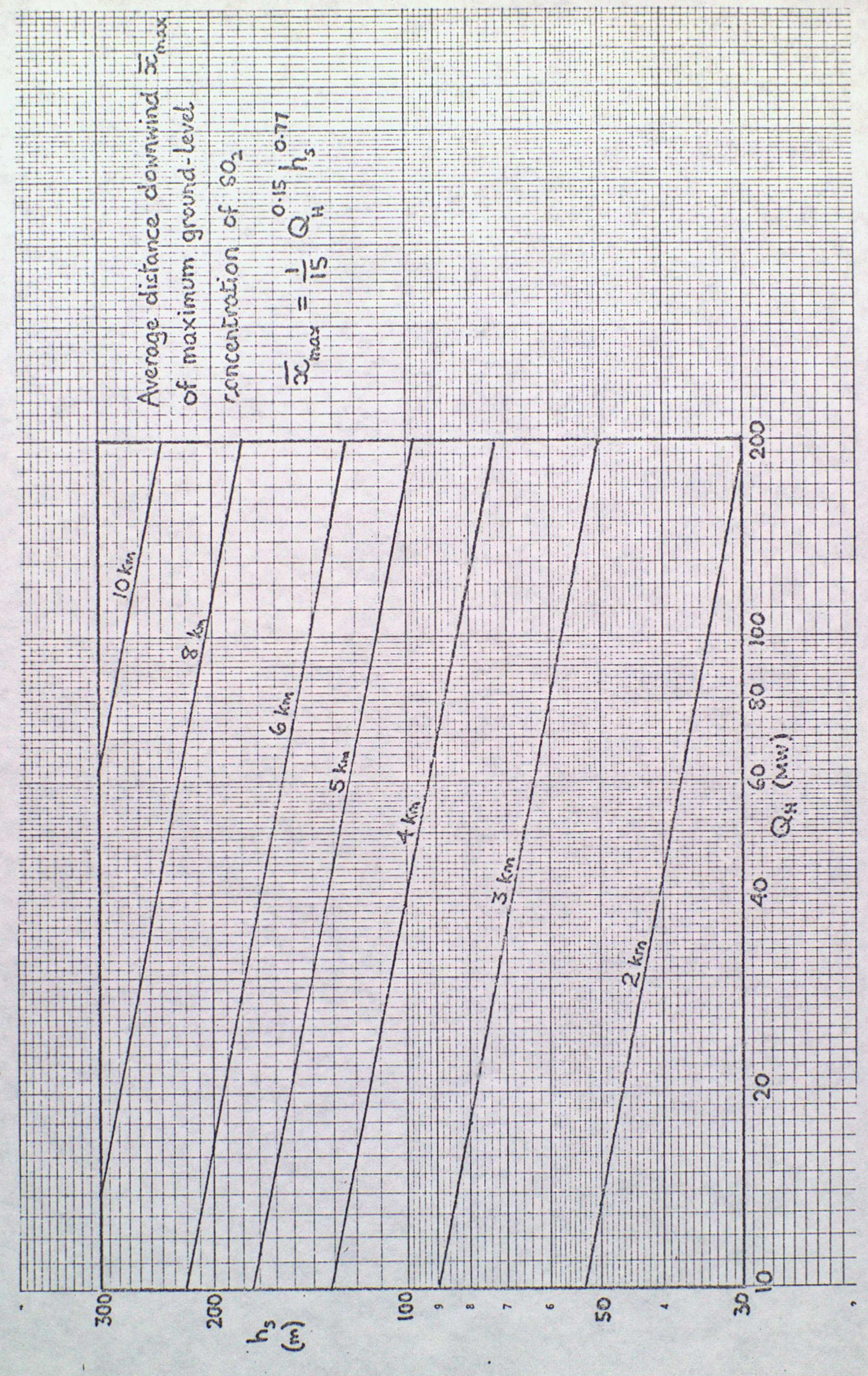
Takes into account the typical variation of Q_{SO_2} & Q_H with u & P. Curves based on Moore's data for Northfleet & Tilbury P.S.

Figure 10.



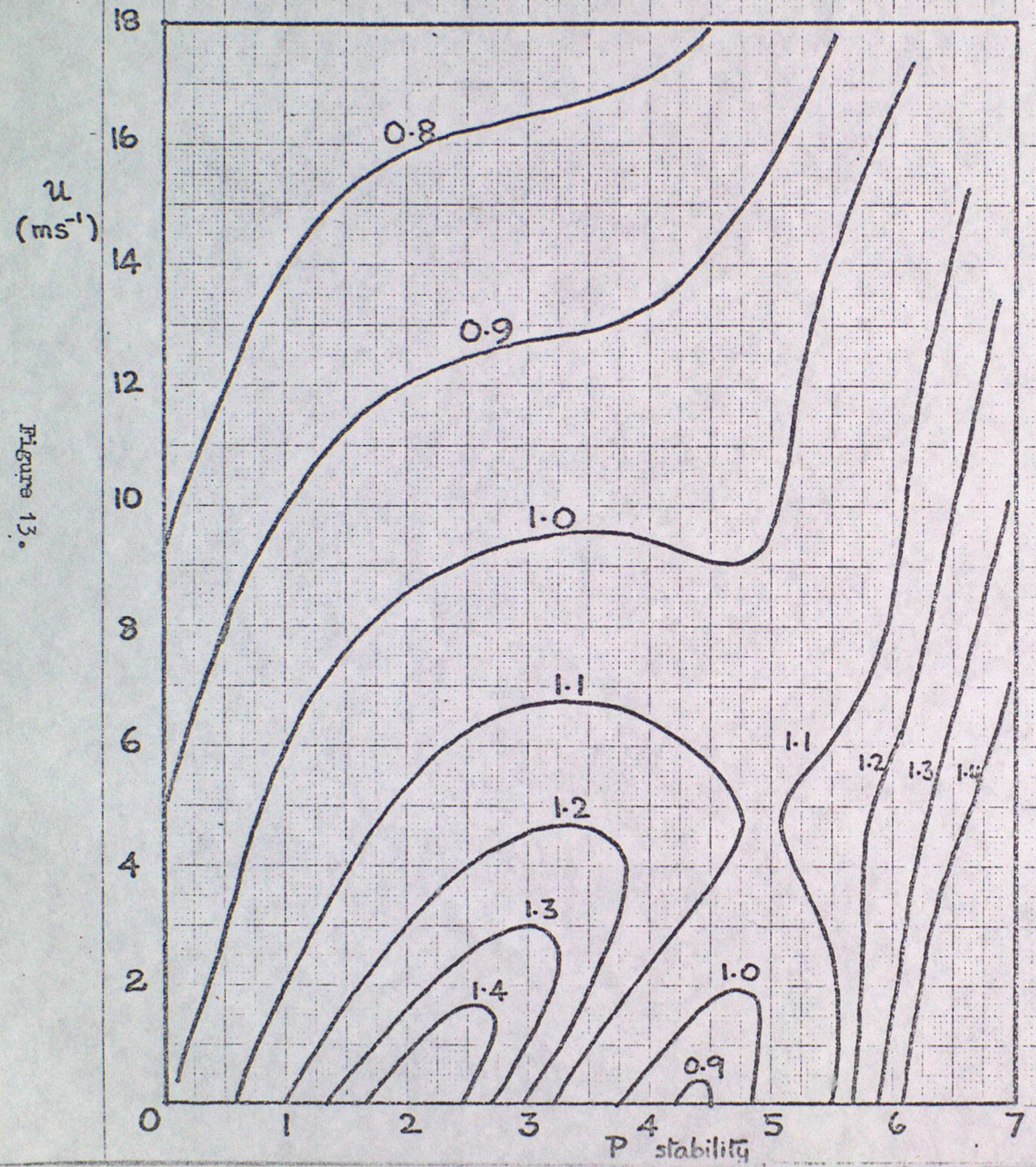
3·0
2·5
2·0
1·5
1·0
0.5
0
$\frac{\overline{C}_{max}(T)}{\overline{C}_{max}(1\,hr)}$
not allowing for instantaneous plume width
allowing for instantaneous plume width.
Variation of maximum concentration with sampling time T.
3min
10min
1 hr
6 hr
1 day
2 days
SAMPLING TIME T

Figure 11.



Average distance downwind $\bar{x}_{max}$ of maximum ground-level concentration of SO_2
$\bar{x}_{max} = \frac{1}{15} Q_H^{0.15} h_s^{0.77}$
10 km
8 km
6 km
5 km
4 km
3 km
2 km
10
20
40
60
80
100
200
Q_H (MW)
300
200
100
9
8
7
6
50
4
30
h_s (m)

Figure 12.



CONTOURS OF

$$\frac{x_{max}}{\overline{x}_{max}}$$

where:

$$\overline{x}_{max} = \frac{1}{15} Q_H^{0.15} h_s^{0.77}$$

in kilometres

and Q_H is in MW (output of heat)

h_s is in metres (stack height)

Figure 13.

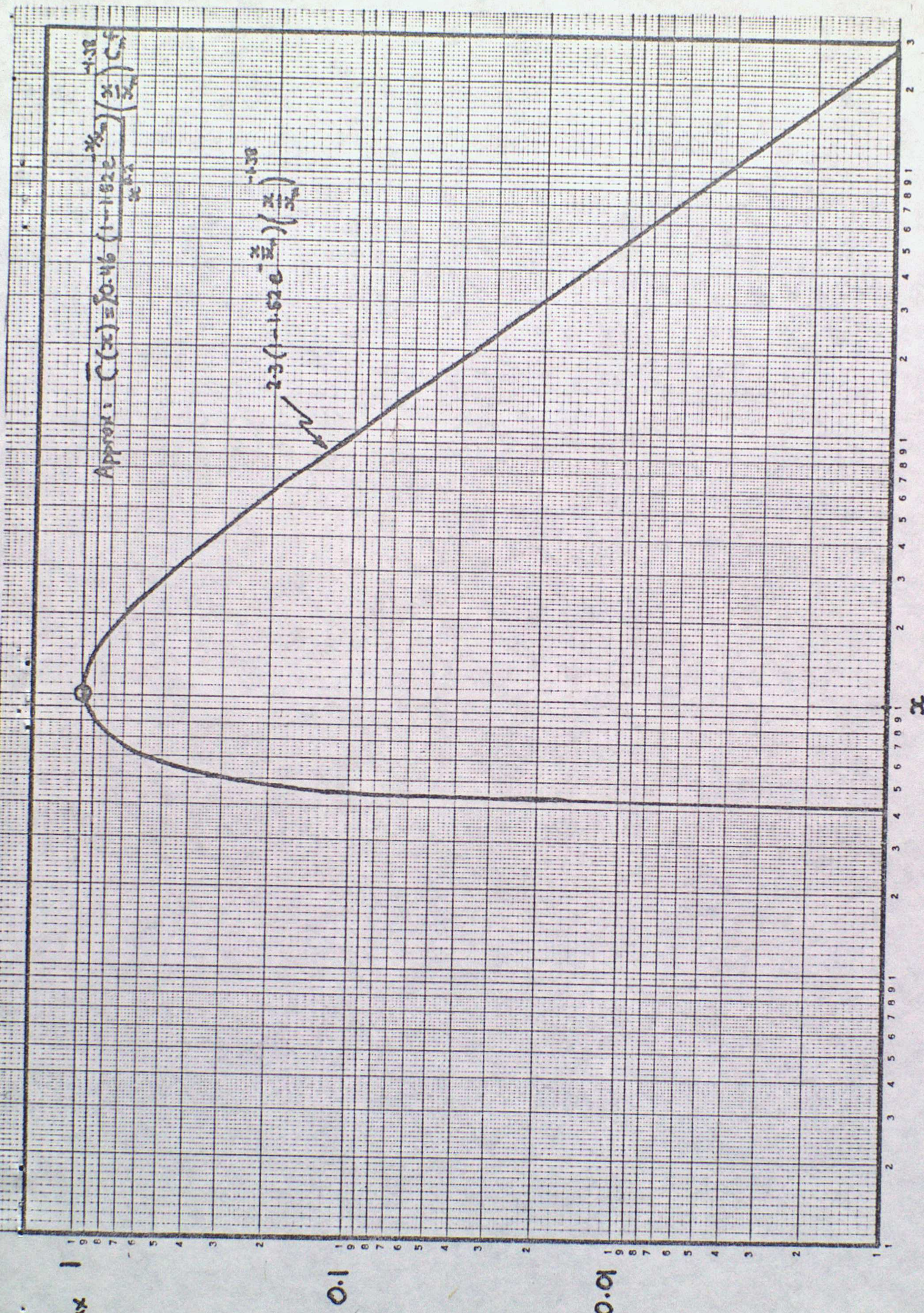


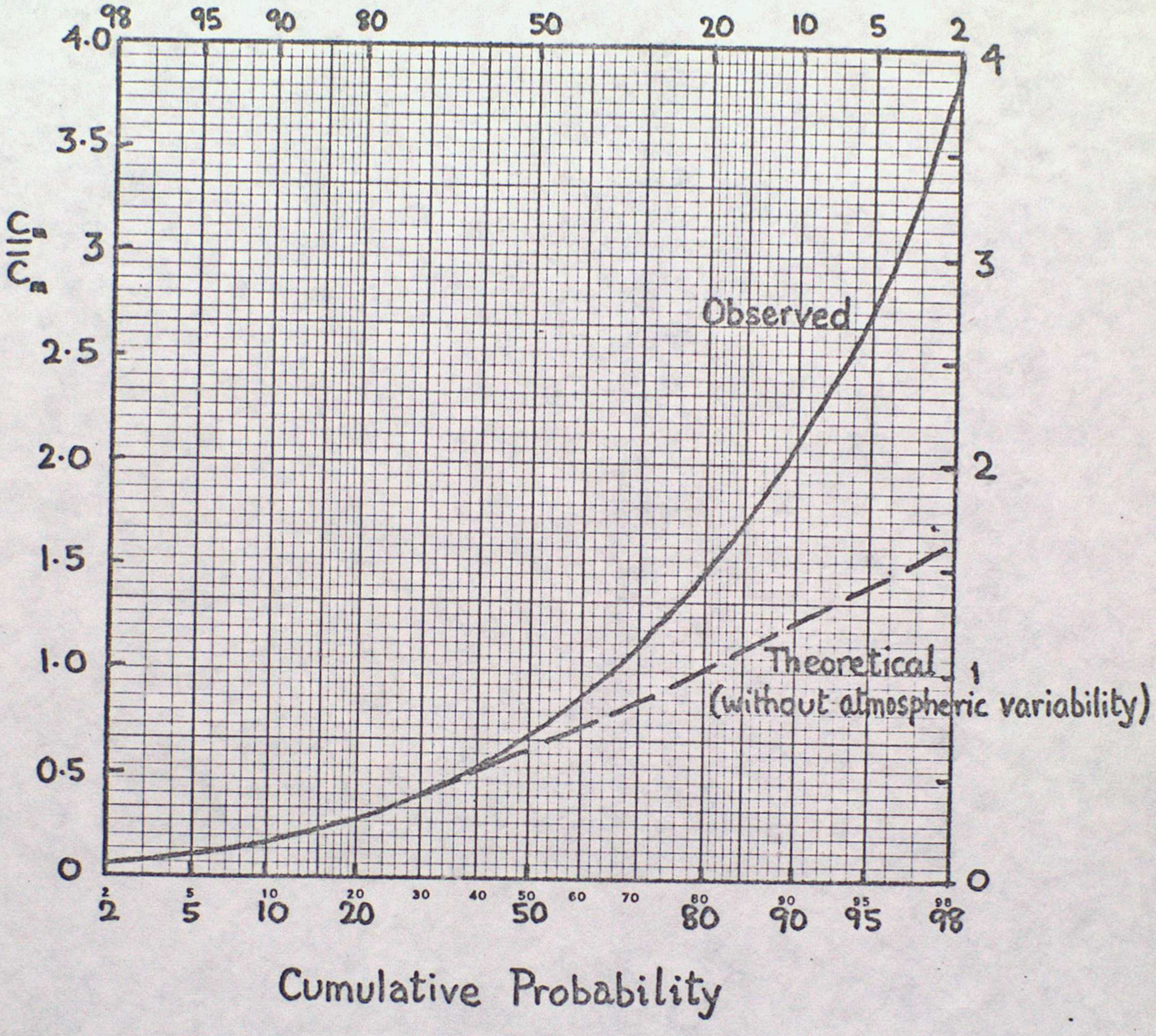
Figure 14.

TYPICAL ERRORS IN C_{max} & x_{max}

due to typical error in u .... ~ 2 ms^{-1}
and in P .... ~ 1 class

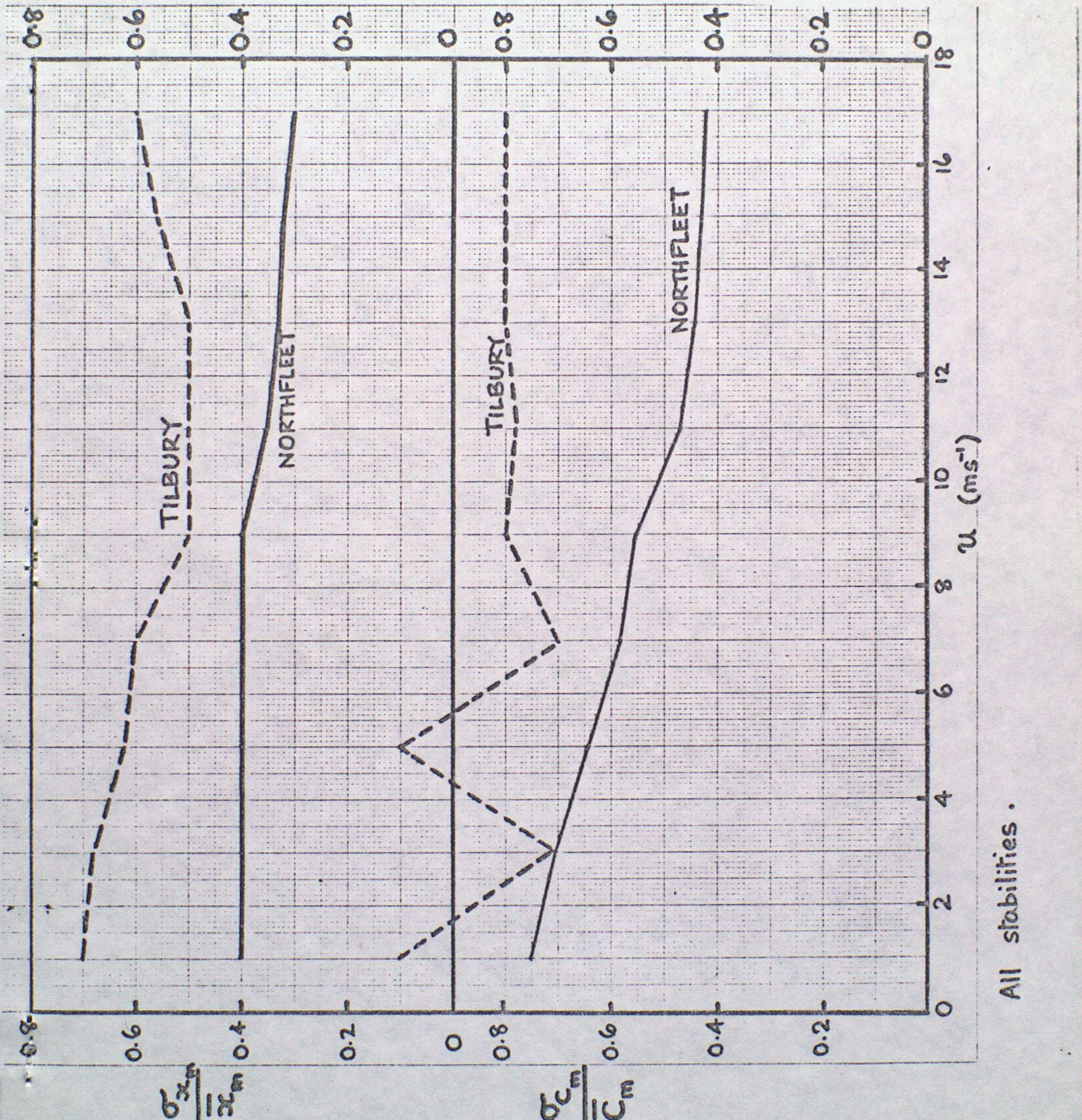
% ERROR	UNSTABLE	NEUTRAL	STABLE
C_{max}	25%	20%	80%
x_{max}	10%	8%	10%

FIG. 15.



This figure shows that variability in maximum ground-level concentration arising from variability in boundary layer structure and turbulence dominates over that due to variations in $C_{max}(u,P)$.

Figure 16.



TILBURY
NORTHFLEET
TILBURY
NORTHFLEET
$\frac{\sigma_{x_m}}{\bar{x}_m}$
$\frac{\sigma_{c_m}}{\bar{C}_m}$
0
0.2
0.4
0.6
0.8
0
2
4
6
8
10
12
14
16
18
u (ms^{-1})
All stabilities.

Figure 17.

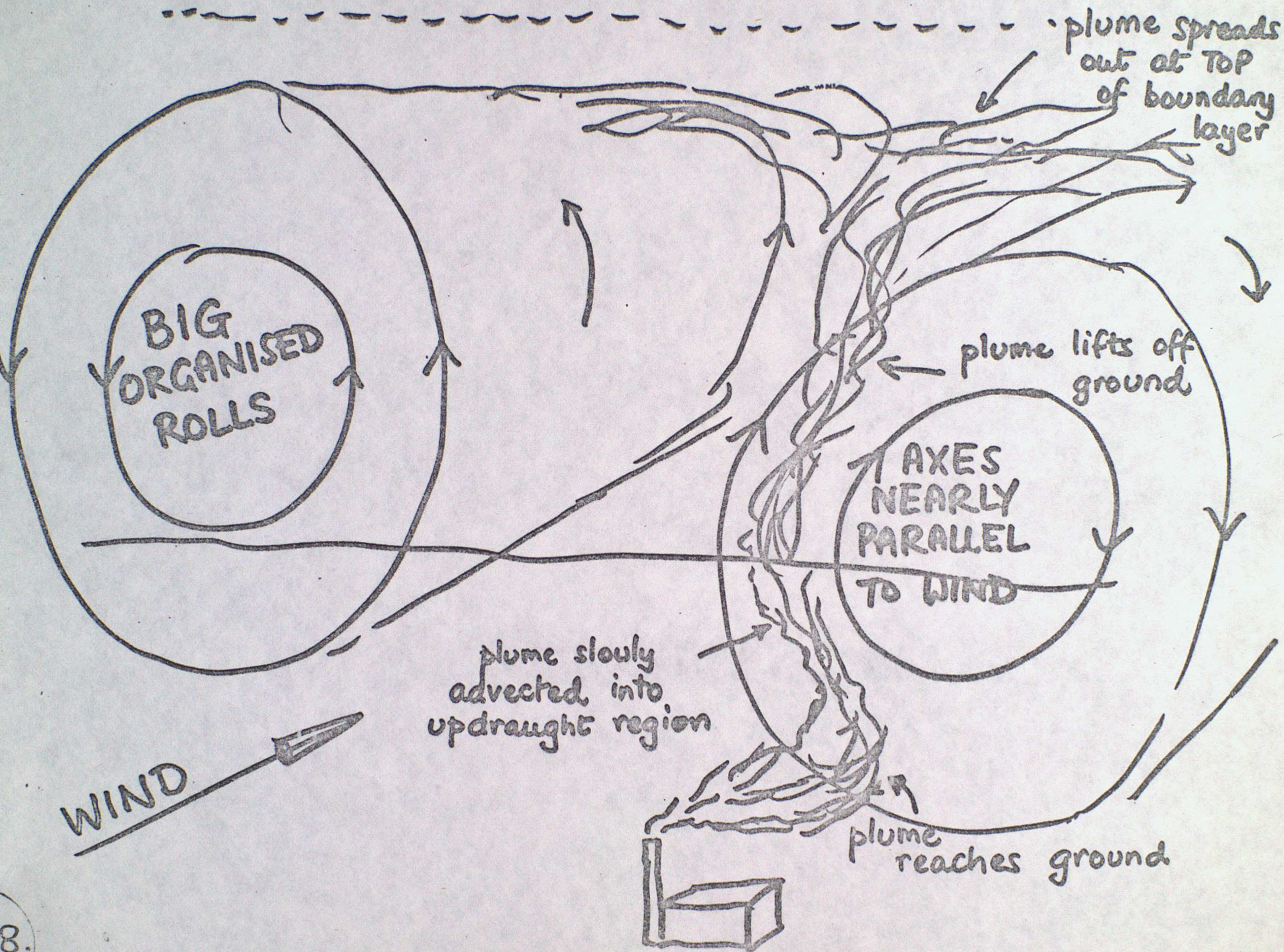
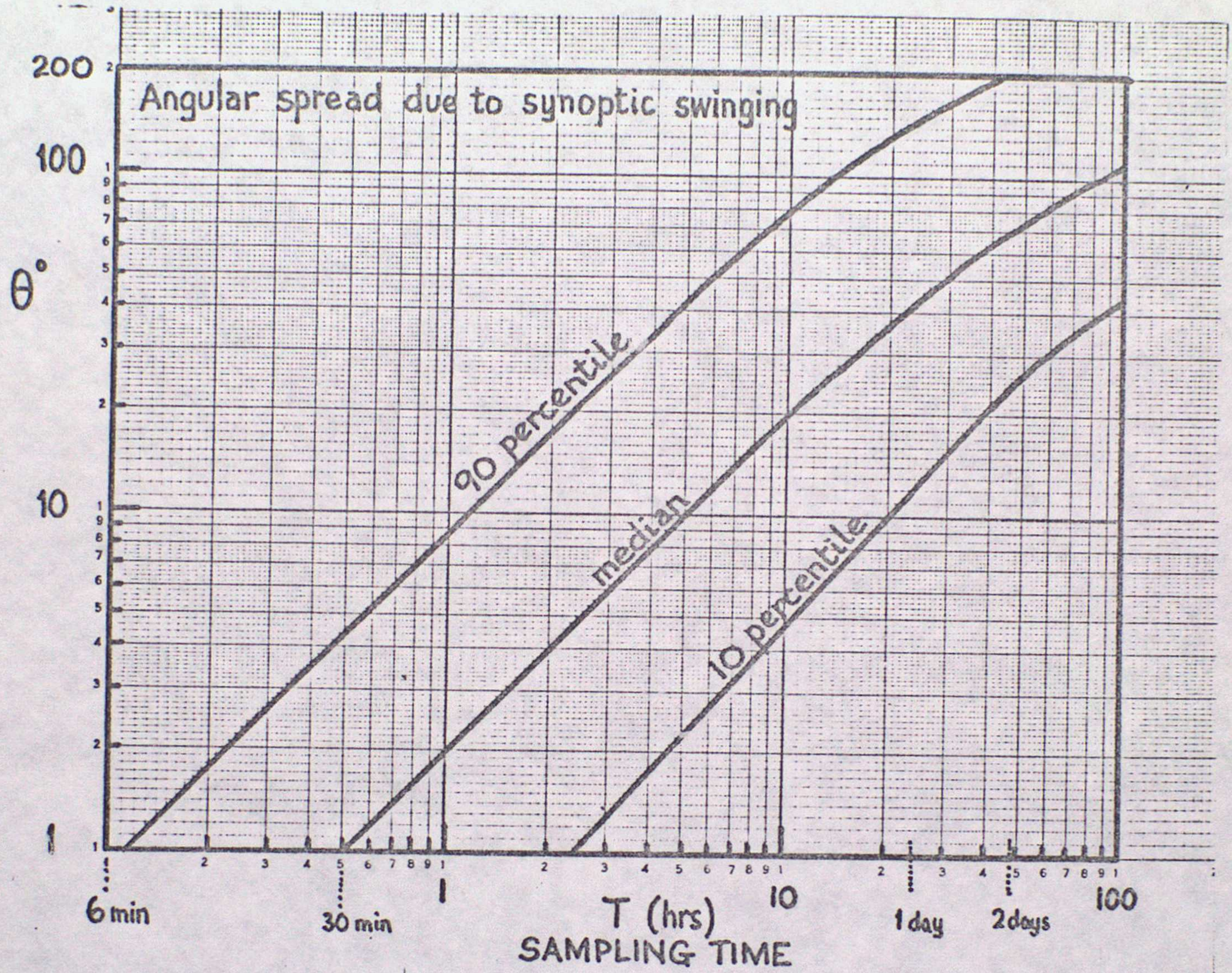

plume spreads out at TOP of boundary layer
BIG ORGANISED ROLLS
plume lifts off ground
AXES NEARLY PARALLEL TO WIND
plume slowly advected into updraught region
WIND
plume reaches ground

FIG. 18.



Angular spread due to synoptic swinging
200
100
10
1
θ°
90 percentile
median
10 percentile
6 min
30 min
1
10
1 day
2 days
100
T (hrs)
SAMPLING TIME

Figure 19.