NRPB-R199

The Seventh Report of a Working Group on Atmospheric Dispersion

The Uncertainty in Dispersion Estimates Obtained from the Working Group Models

J A Jones
Chairman of the Working Group

National Radiological Protection Board

Chilton, Didcot, Oxon OX11 0RQ
August 1986

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UNITS

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Quantity	New named unit and symbol	In other SI units	Old special unit and symbol	Conversion factor
Exposure	–	$C\ kg^{-1}$	röntgen (R)	$1\ C\ kg^{-1} \sim 3876\ R$
Absorbed dose	gray (Gy)	$J\ kg^{-1}$	rad (rad)	1 Gy = 100 rad
Dose equivalent	sievert (Sv)	$J\ kg^{-1}$	rem (rem)	1 Sv = 100 rem
Activity	becquerel (Bq)	s^{-1}	curie (Ci)	$1\ Bq \sim 2.7 \times 10^{-11}\ Ci$

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ABSTRACT

This report is the seventh in a series giving practical guidance to estimate the dispersion of radionuclides released to the atmosphere. It represents the conclusions of a Working Group established to review recent developments in atmospheric dispersion modelling and to propose models for use within the UK. This report examines the uncertainty inherent in predictions of atmospheric dispersion made with models recommended by the Group. It identifies a number of sources of uncertainty, such as the random nature of atmospheric dispersion, the idealisations inherent in modelling and the choice of values for the many parameters involved. The report puts these uncertainties in context and comments on the reliability of models for use in practical situations.

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FOREWORD

In December 1977 a meeting of representatives of UK government departments, utilities and research organisations was held to discuss methods of calculation of atmospheric dispersion for radioactive releases. Those present agreed on the need for a review of recent developments in atmospheric dispersion modelling, and a Working Group was established to facilitate the review. The Group has published six reports so far.

The first report gives practical guidance on estimating the dispersion of radioactive releases in the atmosphere within a few tens of kilometres of the release point, for both short duration and continuous releases. That report dealt specifically with radionuclides which do not deposit on the ground and are not removed from the plume by interaction with rain. The second report describes methods for including dry and wet deposition in the models given in the first report, while the third report describes an extension of the models to long range dispersion from a continuous release. The fourth report describes a model for long range dispersion from a short release. The fifth report describes ways in which the models given in the earlier report can be extended to allow for effects of coastal conditions, buildings and plume rise on the dispersion of material, and gives guidance on the value of deposition velocity and washout coefficient for use in the models given in the second report. The sixth report examines the problems inherent in modelling wet deposition from a short release. It extends the scope of the second report which gave a model for wet deposition primarily applicable to a continuous release.

This report, the seventh by the Group, examines the uncertainty inherent in model predictions and identifies the reasons for that uncertainty.

The membership of the Working Group for most of the period in which this report was being prepared was:

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PREVIOUS REPORTS BY THE GROUP

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Jones, J A, The second report of a Working Group on Atmospheric Dispersion: a procedure to include deposition in the model for short and medium range atmospheric dispersion of radionuclides. Chilton, NRPB-R122 (1981) (London, HMSO).

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Jones, J A, The fourth report of a Working Group on Atmospheric Dispersion: a model for long range atmospheric dispersion of radionuclides released over a short period. Chilton, NRPB-R124 (1981) (London, HMSO).

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Jones, J A, The sixth report of a Working Group on Atmospheric Dispersion: modelling wet deposition from a short release. Chilton, NRPB-R198 (1986) (London, HMSO).

1. INTRODUCTION

A prediction of concentration or deposition rate made using the models recommended by the Working Group on Atmospheric Dispersion Modelling is unlikely to be exactly that observed in any given situation. This discrepancy, termed uncertainty in this report, stems from a number of aspects of dispersion modelling. This report describes the sources of uncertainty and attempts to quantify the uncertainty in predictions made using the models given by the Working Group and to state the situations for which the models are appropriate. The uncertainty in model prediction is estimated by considering both the uncertainty in parameter values and results of experiments carried out to validate similar dispersion models. The report concentrates on the use of the models recommended by the Group for predictions in UK conditions. This restriction to UK conditions can influence the possible range of values of some of the meteorological parameters. It may also influence the ranking of effects as contributors to the overall uncertainty. In some cases a more complex model or parameterisation is indicated if its use may lead to an improvement in accuracy or reduction in uncertainty.

2. SOURCES OF UNCERTAINTY IN DISPERSION PREDICTIONS

Any prediction of concentration or deposition obtained from a dispersion model has some uncertainty associated with it. The uncertainty stems from a number of sources, as illustrated in Figure 1. These different sources of uncertainty, and possible ways of reducing it, are considered in this section.

Atmospheric dispersion is governed by the prevailing meteorological conditions and turbulent motions in the atmosphere and is therefore a random process. This means that a series of releases in similar atmospheric conditions would give a range of observed concentrations. Dispersion models are derived to predict the mean of this ensemble and therefore there will be some discrepancy on any specified occasion between the predicted and observed concentration, even if the model is capable of giving a perfect prediction of the mean. The uncertainty arising from the random nature of turbulence and the natural variability of the atmosphere may, in some cases, be quantified, but can never be eliminated.

A dispersion model must include some idealisation of the processes involved in dispersion. This idealisation may introduce a systematic bias into the model by not adequately considering an important part of the process. The aim of the Working Group has been to identify models which minimise this bias for specified conditions; these models have been described in the Group's earlier reports and are summarised in Section 3 of this report.

A further contribution to uncertainty in the models, identified as numerical error, is included in Figure 1. This is the error introduced if the numerical implementation of the model is not exact, for example in integrals which have to be evaluated numerically or in the effects of finite grid size in numerical solutions of the diffusion equation. The only case where this could significantly affect the models recommended by the Group so far is the calculation of plume depletion due to dry deposition, especially for a source at ground level.

The uncertainty due to what is termed the 'adequacy of model parameters' is best illustrated by an example. The Gaussian plume model is acceptable in many situations where it is possible to describe the distribution of material by the parameters σ_y and σ_z. However, relating these to atmospheric conditions through a single stability parameter may introduce an error which could be avoided if a more complex parameterisation of the boundary layer were to be used. This uncertainty might be reduced by using a sufficiently detailed model of the structure of the boundary layer or if site-specific parameter values are available. σ_y and σ_z would then be functions of more than one parameter.

The final type of uncertainty considered here is that due to the values assigned to the many parameters required in dispersion modelling. Uncertainty can arise from measurement error (eg, a badly aligned wind vane), or from the use of unrepresentative values for parameters. These could be unrepresentative of the general situation for a number of reasons, eg, wind speed and direction may have been obtained from an anemometer which is affected by topographic features other than those affecting the plume, or the deposition velocity derived for particles with a fixed size may have been used for an aerosol with a wide range of sizes but the same average size. The range of values which might reasonably be selected for most of the parameters considered in the models suggested by the Group is considered in Section 4 of this report.

3. APPLICABILITY OF THE MODELS

The choice of dispersion model, and the choice of the values for its parameters, depend to some extent on the use to be made of the model predictions. Models for calculating concentrations and depositions due to short releases could be designed to meet a number of objectives, such as

- predicting the most probable values resulting from a number of short releases in similar atmospheric conditions (ie, the ensemble average)
- predicting the range and probability distribution of values resulting from a number of releases in similar atmospheric conditions
- predicting the values due to a single release at a known (past or current) occasion when atmospheric conditions can be specified
- demonstrating that the values following release of a specified amount of material are unlikely to exceed stated levels.

Models for continuous releases can be designed for similar objectives.

These different applications of a model are best illustrated by an example. Suppose a tracer experiment was carried out in which material was released for a given duration whenever the atmospheric stability was considered to be in a specified category. Clearly there would be a distribution of observed concentrations from these releases. The first of the aforementioned applications of dispersion models is to calculate the most probable value of this distribution. Some of the variation between the results of different releases will be caused by differences in the prevailing atmospheric conditions. In the example given, there could be a range of wind speeds within the chosen category or some of the releases may have been in a category other than the one intended. The second application of a model is to predict the probability distribution of concentration using the likely or typical range of parameter values. The third application of a model is to predict the concentration from a specific release using parameter values which were actually measured during the release period.

The final application of a model is somewhat different and can be undertaken in one of two distinct ways. If the complete probability distribution of concentration is calculated, as in the second application, then it is a simple matter to evaluate the probability of exceeding a particular concentration. Alternatively, it may be possible to carry out a simple, but pessimistic, calculation to demonstrate that concentration is unlikely to exceed the given reference value. This latter approach is easier for concentration close to a source than at larger distances, as formulation of a pessimistic model is then relatively straightforward.

The models proposed by the Group are intended mainly for the first of these uses, namely to predict the most probable concentration for a release in given conditions. Realistic values of the parameters are suggested, and the models are intended to give a realistic estimate of the concentration. The models can be used to predict the range of concentrations likely to be encountered in a given situation by using a range of values for the parameters involved. The model will only predict the complete range of concentrations if all relevant processes are included in the model. Most models include some implicit averaging in their treatment of the dispersion process and so may be unable to describe conditions in some circumstances. A suitable choice of parameter values will enable a prediction of the maximum likely concentration or deposition to be made provided the model considers the relevant conditions. The variation of prediction with parameter value is rarely monotonic so that the peak concentration or deposit may not be predicted for the maximum or minimum value of the parameter considered. The use which is to be made of predictions must therefore be considered when selecting values for the parameters in the model.

The Group's reports have specified a number of caveats on the use of the recommended models. This section summarises those earlier warnings and tries to give a more quantitative statement of the conditions for which the models are expected to have the minimum systematic error. However, there are conditions where only qualitative statements can be made.

3.1 Applicability of the simple Gaussian model

The Group's first report describes a model for use in estimating concentration at short and medium range from an isolated point source. Subsequent reports describe models for calculating dry and wet deposition rates allowing for the effects of plume depletion and of describing long range dispersion. All the models are based on the assumption of a constant release rate and are for a source within the boundary layer. Models for some special situations, ie, coastal sites, buildings near the source and plume rise, have also been considered.

The Gaussian-plume model is clearly not applicable in conditions with zero wind speed and the formula itself diverges because it contains the reciprocal of the wind speed. Its use in conditions of very low wind speed is questionable because the wind speed and direction are very variable in these conditions so that a well-defined plume is unlikely to exist and the assumption that along-wind dispersion can be neglected is no longer valid. The Group suggests that the model should not be used for a wind speed below 1 m s^{-1}.

The Gaussian model is based on the assumption that the vertical wind velocity is zero. This is generally acceptable but may be a source of error when assumed to apply to airflow near hills or to developing internal boundary layers. Problems may also arise if concentrations for very short averaging times are to be calculated since the full range of turbulence scales is not sampled and a time varying vertical wind speed results. This is manifest in the well known phenomenon of 'plume looping' in very unstable conditions.

The models given in the first report are intended for application to dispersion over flat terrain of uniform surface roughness and heat flux. This restriction applies not only to the terrain over which the plume is dispersing but also to the terrain for some distance upwind of the source, as the models are applicable only to a well-established boundary layer. Additionally, there should be no nearby large areas where the underlying surface properties are sufficiently different to change the flow conditions significantly. Such situations can occur near to the coast or to large urban areas. (Special calculations for coastal conditions are described in the Group's fifth report.) The requirement of uniform surface roughness can be relaxed somewhat and expressed as the need for there not to be a significant number of obstacles whose size is such that they modify the levels of atmospheric turbulence. It is very difficult to give quantitative guidance on whether a specific site should be regarded as flat or complex terrain. However, some criteria are given in Table 1, based on the chagne in wind speed between flat and complex terrain not exceeding 30%. It is seen that the criteria depend on the stability of the atmosphere. It is suggested in the table that, in stable conditions, terrain can be regarded as flat if it has an average slope of less than 1 in 100. It should be noted, however, that in very stable conditions terrain effects could be observed with a slope as low as 1 in 1000. Similar guidance can be given on the need to allow for changes in surface roughness. The range of roughness length (z_0) for which the wind speed at 10 m height is within 30% of that for the central value of z_0 for the same geostrophic wind speed is given in Table 2.

The models in the first report are appropriate where the airflow at and down wind from the release point is not affected by nearby buildings. Models for dispersion from a source close to a building are considered in the fifth report, which also describes the conditions in which a source can be considered to be unaffected by major building effects. Material emitted from a stack can be affected by downwash in the wake of the stack itself unless it is discharged with an upward velocity greater than the wind speed at the release point. If the exit velocity is much greater than the wind speed at release height, or the emission contains significant buoyancy, it will cause the plume to rise above its release point. Models for this situation are also considered in the fifth report. The accuracy of models for building effects and plume rise are considered in Section 5 of this report.

The models in the first report are applicable at short and medium distances from the release point. This restriction is imposed by the assumption in the model that atmospheric conditions have not changed during the travel of the plume. The probability that a stability category will persist for a given time is shown in Table 3, from which it is seen that most categories persist, on average, for only a few hours, with a low probability of any category other than D persisting for six or more hours. The travel distance for which the models are appropriate can be estimated from the product of the wind speed and the category duration. In some cases in light wind conditions this may be only a few kilometres. Restrictions on the distance over which the model can be used are also imposed by the requirement that the wind direction has remained constant. Changes in wind direction also occur on a timescale of a few hours, implying for some calculations (eg, concentration at a specified point on a given occasion) a further reduction in the travel distance over which the model can be used. The models are not applicable when the flow field is significantly distorted, for example by the effects of topography.

The time for which steady atmospheric conditions persist imposes restrictions on release durations considered to be short. Releases of longer duration can be treated as sequences of short releases in constant, but different, conditions. Average concentrations over extended periods such as months or years can be obtained using the continuous release model given in the Group's reports.

The values of σ_y and σ_z recommended in the first report are appropriate only for a fairly low-level source. The variation of plume size with release height is considered later.

3.2 Applicability of the model for deposition

The Group's second report describes models for calculating dry and wet deposition rates and the accompanying plume depletion. The assumptions made in modelling depletion due to dry deposition are not applicable to plumes of material which have travelled for long periods in stable conditions and for which the deposition velocity is moderately high. Nevertheless, the Group considered that the method would be appropriate for all atmospheric situations likely to be encountered in practice. However, it is not designed for application to material with a significant gravitational settling velocity and the Group suggested a restriction to aerosols of AMAD* less than about 10 μm.

The calculation of wet deposition from a continuous release is described in the Group's second report, while the sixth report considers wet deposition from a short release. This latter calculation is very difficult because the simple Gaussian model does not include a number of the processes occurring. The Group's report describes the difficulties caused by the spatial and temporal variability of rainfall rate and the vertical air movements within a rainstorm. A number of simple formulae are given in that report, with advice on when they should be applied. The model given in the second report averages over the sequences of dry and wet conditions affecting dispersing material. Its statistical formulation means that it is not applicable to single short releases. No quantitative statement of the uncertainty in wet deposition calculations can be given. Their reliability is likely to increase with increasing spatial and temporal averaging and in persistent light rain.

4. UNCERTAINTY IN PARAMETER VALUES

Before models can be used, values must be assigned to each of a number of parameters, and in almost all cases the values of the parameters are uncertain. This section contains estimates of the range of values which the Group considers would be reasonable for these parameters if the dispersion model is being used to obtain a realistic estimate of the mean concentration from a number of short releases, or the average concentration from a continuous release. Some indication is also given of possible parameter values for other applications. The ranges of values suggested for each parameter are summarised in Table 4.

A comment should be made about the choice of a parameter value from the range of values reported in the literature. Consider the selection of a best-estimate value where the reported values for the parameter are spread uniformly between a minimum and maximum value. If equal weighting is given to all observations, then the representative or best-estimate value will be the middle of the range. The use of a representative value near the high end of the range implies a decision to attribute a low weighting to all observations near the lower end of the range, rather than merely the recognition of the possibility

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*Aerodynamic diameter of a particle is the diameter of a unit density sphere with the same settling velocity as the particle. Activity median aerodynamic diameter (AMAD) of an aerosol is the median of the distribution of activity against aerodynamic diameter.

that the parameters can take a high value. However, the use of a value near one end of the range can sometimes be justified for other applications.

4.1 Wind speed and direction

The choice of a value for wind speed depends on the application for which the model is being used. If the objective is to estimate the range of concentrations possible in a single category then the range of wind speed to be considered can be obtained from Figure 2 of the Group's first report. The range is different in different categories, eg, categories A and G can only occur if the wind speed is less than about 3 $m\ s^{-1}$ while category D could occur for any value of the wind speed. Somewhat narrower ranges would be appropriate if the objective was to estimate the uncertainty on the predicted mean value.

Additional considerations arise if the objective is to predict the concentration on a specified occasion, since this is very sensitive to the assumed wind speed and direction. Smith and Readings(1) have considered the error in estimating the wind speed at a point away from a meteorological station. They estimate errors of about 2 $m\ s^{-1}$ in speed and up to 20° in direction of the wind at a height of 10 m, arising from instrument error and from the extrapolation to other locations within a few tens of kilometres of the measuring point over rolling terrain. The absolute error in wind speed increases with increasing wind speed while that in direction is greatest for low wind speed.

There are complications at low wind speeds arising from instrumental error if a standard anemometer is used, as its starting speed may be comparable to the wind speed. This can lead to difficulties in specifying extremes of stability and the frequency with which they occur.

Errors in wind direction could also arise from a number of other causes, such as using data from a badly aligned or badly sited wind vane, or using a wind direction corresponding to an inappropriate averaging period. The importance of errors in wind direction depends on the application of the model. Predictions of the concentration from a single release at a point are clearly very sensitive to wind direction because of the need to predict the position of the plume centre-line. However, for many applications in radiation protection only the peak centre-line concentration, and not its location, needs to be predicted.

The Group's model for short releases uses the wind speed at 10 m height in estimating concentrations. However, for continuous releases the Group recommends the use of wind speed at the height of the source, and gives in its first report a formula for the variation of wind speed with height. This extrapolation will produce further uncertainty in the estimated concentration. The formula given in the Group's report is a simplified one, only applicable to the lower parts of the mixing layer. More general formulae for the wind velocity profile throughout the mixing layer are given by Smith and Blackall(2) and by Irwin(3), these papers being in reasonable agreement. In stable conditions the wind profile is more strongly dependent on stability than surface roughness, whereas the opposite tends to be the case in unstable conditions. In strongly stable conditions with a low lying inversion the wind velocity at the height of a tall stack may be very different from that near ground level.

A further complication, especially if the objective is to predict the concentration on a specific occasion at a specific point, is the change in mean wind direction with height. This could cause material to be carried in a direction other than that indicated by a nearby anemometer.

4.2 The stability category and its frequency distribution

The uncertainty in the stability category assigned on any specified occasion can be determined from the uncertainty in the wind speed considered above and the uncertainty in the sensible heat flux.

The sensible heat flux is required to deduce the stability category. It is a derived quantity which cannot easily be measured directly but whose value must be estimated. The method suggested in the first report is a very simple one in which sensible heat flux is derived from the incoming solar radiation and which does not consider the type of underlying surface. Smith and Hunt(4) have compared the predicted sensible heat flux with measurements made at Cardington. They conclude that the error on the value predicted in daytime conditions using this scheme is ±55 W m^{-2} when the mean flux was 81 W m^{-2}. Smith and Blackall(2) describe a more complex model applicable to grassland in which more detailed information on the state of the surface is used. This model gives a more accurate prediction of the sensible heat flux than does that given in the Group's first report. There is a further error on a specific occasion in assuming that the value at the meteorological station is the same as that at the plume position.

In general, the assigned stability category is unlikely to be in error by more than one category if based on observations at the point. However, the error described above in estimating wind speed away from a meteorological station implies a greater uncertainty in the category.

The calculation of concentration from a continuous release requires the specification of the joint frequency distribution of wind speed, direction and stability over the period of the release. The frequency distributions observed at a meteorological station differ from year to year, so that the concentration predicted from many years' data may not be the same as that predicted from a single year's data. Predictions of concentrations from a future continuous release could be uncertain because of temporal changes in these frequencies. The frequency distributions obtained at a specific meteorological station may also depend on the frequency with which the station reports.

4.3 Depth of the mixing layer

The mixing layer depth can be obtained in a number of ways, the choice depending on the intended application of the model. If the objective is to predict the average concentration from a release in a specific category then the mixing layer depth used must represent the average in that category. The Group's first report suggests average values of mixing layer depth in each category, and quotes an uncertainty represented by a standard deviation of about 250 m for each of categories A to D. This estimate is based on the work of Carson(5) and represents an estimate of the difference between observed and predicted depths for a specific time when all other relevant parameter values were known. The uncertainty on mixing layer depth in stable conditions can be estimated from models described by Venkatram(6) and by Pasquill and Smith(7). They present data suggesting that the uncertainty on mixing layer depth at a given time is unlikely to exceed 50%. The uncertainties specified above are the differences between observed and predicted values at specific times. The uncertainty on the mean value selected in similar meteorological conditions implies that some averaging has taken place and would be less than these ranges. However, the mean value for a stability category must reflect the range of conditions encompassed by that category, and hence could have a larger uncertainty than that for a given time.

4.4 Vertical standard deviation, σ_z

As the atmosphere can exist in any state from 'super A' to 'extreme G' it seems reasonable to suppose that σ_z at a given distance can take any positive value, including some larger than that for category A and some less than that for category G. The stability categories merely represent portions of this continuous distribution. It seems reasonable to assume that σ_z for the category being considered can be distributed equally between points mid-way between those values representative of the category itself and the adjacent categories. If the objective is to predict the distribution of concentration for a release in a specific category then the uncertainty on σ_z must reflect this complete range. If, however, the intention is to predict only the mean concentration then the uncertainty on σ_z is much less as the mean value is unlikely to be near the extremes of the total range possible. This estimate of the uncertainty on σ_z assumes that the category has been correctly assigned.

The value of σ_z depends on the height of the source, with the values given by the Group being appropriate to a fairly low source. In stable conditions, plumes from sources above the inversion often expand to a maximum depth of no more than about 10 m; for a release below the inversion it may be possible to interpolate between the recommended values of σ_z for a ground-level source and an assumed value of 10 m at the height of the inversion. In very unstable conditions (ie, category A), for distances less than about 1 km, experiments suggest that σ_z for ground-level sources is proportional $x^{3/2}$ but for releases at heights above about 100 m varies more directly as x. Beyond about 1 km the rate of increase of σ_z with distance reduces. The maximum expansion of the plume in the first kilometre is no more than half the depth of the boundary layer.

4.5 Horizontal standard deviation σ_y

The formulation of horizontal dispersion recommended in the Group's first report distinguishes between horizontal plume growth caused by small-scale atmospheric turbulence and by larger scale wind-direction fluctuations. These different contributions to σ_y, with different uncertainties, make the overall uncertainty strongly dependent on sampling time.

The uncertainty on the turbulence component σ_{yt} can be estimated by similar considerations to those used for the vertical component σ_z, as the two parameters are likely to be strongly correlated. It therefore lies in the range of values midway betwen that of the assigned stability category and the adjacent categories.

The uncertainty on σ_{yw}, the spread due to wind direction fluctuations, can be derived from work by Moore(8). He compared predicted and observed peak concentrations, quoting a ratio of 1.0 ± 0.6, for individual hourly readings and 1.0 ± 0.2 for the ensemble average, the error being 1 standard deviation. Since peak concentration occurs approximately at the distance at which $\sigma_z\surd 2$ equals the effective release height, it is reasonable to infer that the uncertainty given above is primarily that on σ_y, and can be taken as the upper limit of uncertainty on σ_{yw}.

If the model is being used to predict the concentration at a specific past or current time, then the use of a measured value of σ_θ (the standard deviation of wind direction fluctuations) will give a more accurate prediction of concentration than the use of a standard σ_y value for the ambient conditions.

One aspect of horizontal plume spread not explicitly considered in the Group's reports is the effect of wind shear, that is the variation of wind direction with height. The Group's recommendations are appropriate for typical variations of wind direction with height which are taken into account in the formulation of σ_y and σ_z. The recommended values should not be used for cases with very large wind shear, as may occur in very stable conditions or near complex terrain.

4.6 Deposition velocity

This topic has been extensively reviewed by a number of authors (McMahon and Denison(9), Sehmel(10), Slinn(11) and Underwood(12)). The Group has recommended that the variation of deposition velocity with the size and chemical form of the depositing material be considered. Deposition velocity also depends on underlying surface and wind speed. Ignoring this variation, as suggested by the Group, could increase the uncertainty of a prediction.

The Group, in its fifth report, recommended that the value of deposition velocity for a 1 μm particle was between 10^{-4} and 10^{-3} m s^{-1}. This was intended as an estimate of the value for use in assessing the most probable deposition from a release. If the objective is to assess the range of possible depositions from a release then a wider range of values would be required. Because the deposition velocity is a minimum for particle sizes near 1 μm, the value chosen for an aerosol with a range of sizes would most probably be greater than the value given above.

The Group also recommended a range of values for deposition velocity of elemental iodine ranging from 10^{-3} to 10^{-2} m s^{-1}. As with particulate material, this range was intended for calculating the average deposition from a release and a larger range would be required in order to predict the range of possible deposition rates.

Sehmel's(10) review distinguishes between experiments in which the deposition velocity was deduced from plume depletion measurements and those in which it was obtained from measurements of air concentration at a low level and the accompanying deposit. The former type of experiment tends to give a lower value than the latter type.

Changes in the physical and chemical form of the airborne material after its release should be considered when selecting values for deposition velocity and washout coefficient. Such changes are more likely to occur for a reactive gas than for other material and for any material except noble gases if large quantities of water in the form of steam or as droplets accompany the release.

4.7 Washout coefficient

The theoretical and experimental information on washout coefficient has recently been reviewed by Brenk and Vogt(13), McMahon and Denison(9) and Underwood(12), among others. The available information was reviewed by the Group in its sixth report.

The theory of washout of particles suggests that the washout coefficient is a function of particle size, rainfall rate and the raindrop size distribution. This latter variation implies that it may differ according to the type of rain (ie, orographic, frontal or convective). Experimentally, the variation with particle size and rainfall rate are unclear. The Group has suggested that the washout coefficient for particles, Λ, should be taken as

$$\Lambda = aR^b$$

where R is the rainfall rate in mm h^{-1}

and a and b are constants.

The Group suggested that the likely value of a is between 3 10^{-5} and 3 10^{-4} s^{-1}, while that for b is between 0.7 and 0.9 for calculating the most probable value of deposition. A wider range would be applicable if the intention was to calculate the range of possible depositions.

The selection of a value for washout coefficient of iodine is complicated by the chemical form of the iodine and possible effects of the reversible nature of the interactions between iodine and water. The uncertainty is greater than that suggested above for particulate material.

4.8 The importance of uncertainty in parameter values

This section has reviewed the likely ranges of uncertainty in the value of the parameters in the models. No general statement can be made about the uncertainty in the predicted concentration or deposit resulting from this parameter uncertainty because of the way in which the different parameters contribute to the results. Thus, air concentration at short distances from the release will not be sensitive to the selected value for the deposition velocity as plume depletion is small. However, at large distances the uncertainty in plume depletion may be the most important source of uncertainty in predicted concentration. Similarly, the concentration at short distances from a tall stack is very sensative to σ_z, while that from a short stack is much less so. The user must examine the uncertainty in the model predictions for the situation of interest to him.

5. THE UNCERTAINTY IN MODELS FOR SPECIAL EFFECTS

Models for dispersion in special situations are generally more uncertain than those for dispersion over level ground. The likely accuracy of the models proposed by the Group in its fifth report for plume rise, building effects and coastal effects is considered in this section. In some cases clear and quantitative statements can be made while in others the discussion must be more qualitative.

There is some information available to allow general remarks to be made about the performance of a model in some special situations. However, the evidence is too sparse to allow general comments to be made on combinations of effects, such as a hill near the coast. Despite this, a user may be able to obtain some information on the likely uncertainty in his special situation from the following sections.

5.1 Plume rise

The plume-rise formulae given in the fifth report apply to emissions from isolated stacks. Moore(14) analyses the performance of his formula and shows that for a plant with heat emissions in the range from about 10 to 170 MW the calculated plume rise equals the ensemble averaged observed values and that the mean error is about 13% of the total calculated plume height. No systematic bias with distance was found. A tendency to overpredict rise for low and high heat emissions and at low wind speeds was revealed.

No model was proposed by the Group for the rise of plumes emitted at ground level or from building wakes. For these cases, limiting dimensionless buoyancy and momentum flux ratios were given to indicate circumstances in which plume rise could be ignored, based on the criterion that ground-level concentrations would be reduced by less than a factor of two. The limit values should only be treated as guide lines to possible behaviour, and any situation in which they are approached within a factor of two or three treated with caution. Wind tunnel tests may be required if it is necessary to quantify the effects of emission buoyancy and momentum.

Almost all work on plume-rise modelling has concentrated on predicting the trajectory of the plume centre-line. However, a rising plume entrains air into itself thus affecting the rate at which it grows. The Group, in its fifth report, gave a formula for the enhanced spread of a plume due to its rise. In view of the limited information available on this topic, the formula must be considered uncertain though it is not possible to quantify the uncertainty.

5.2 Building effects

Building effects were considered in the fifth report and a virtual source model was recommended for use at distances greater than five times the building height. A near-wake model was described for the region between one and five building heights down wind. Both models only apply to passive emissions from or below roof level. No calculation methods were presented for other release points, though complex models were identified for some applications. The use of physical models was proposed for circumstances (1) not covered by the mathematical models, (2) in which their use is open to question or (3) when greater accuracy is required.

The accuracy of the virtual source model has been examined by Fackrell(15). Its performance was shown to be generally conservative, occasionally underpredicting by a factor of two or three, though frequently overpredicting by substantial amounts. The model does not correctly predict variations with wind direction or source position, being designed to simulate conditions leading to the highest ground-level concentrations. This is also true of the near-wake model, though in this case somewhat greater underprediction may occur, up to a factor of four (eg, see Foster and Robins(16)).

5.3 Coastal effects

In the fifth report, two models are put forward to calculate dispersion in the special conditions which can occur near the coast. One describes behaviour when a sea-breeze is blowing and the other the effects of roughness and stability changes at the coast. The latter was recommended for dispersion from a point source within a few kilometres of the coast in all conditions and at all distances if a sea-breeze is not blowing, otherwise the sea-breeze model should be used at larger distances. For dispersion affected by buildings, it was proposed that these extra effects be ignored, though the sea-breeze model could be used for distances beyond those for which building effects are important. The importance of the sea-breeze is its ability to carry material well inland with limited vertical dispersion. However, data for the frequency of penetration of sea-breezes shows, typically, that they reach 50 km inland about 5 times a year, and 100 km less than once a year in the UK. Consequently, they need only be considered when calculating the effects of short duration emissions.

Generally, in a sea-breeze over the UK, the effect of the reduced vertical mixing in increasing concentrations is more than offset by the increased wind speed. For emissions of duration 30 minutes or more, the lateral spread is little different from what it would have been in the absence of the breeze and, consequently, concentration levels are little different. However, for emissions which last only a few minutes, lateral spread is solely determined by the turbulence, and concentrations would be enhanced by factors of about two. Ignoring sea-breeze effects would seem, in general, to be justified, except for very short duration emissions, and then for only a few occasions in a year if transport over distances in excess of 50 km is of interest. Inclusion of sea-breeze effects in probabilistic risk assessment codes has been found to be unlikely to produce a significant change in resulting consequence predictions(17).

Scriven(18) has analysed the effects of (fixed height) inversions on ground-level concentrations and concluded that the maximum might be doubled by an inversion at the source height, the increase falling to less than 20% if the inversion height rises to 30% above the source. A small amount of leakage through the inversion was shown to reduce significantly its influence on ground-level concentrations. In the far field, concentrations under a low-level inversion situation would be greater than otherwise, in proportion to the ratio of the normal mixing layer height to the inversion height. In the majority of cases of sources within internal boundary layers capped by an inversion, increases will be less than this because of the growth of the layer between the emission point and the point of maximum ground-level concentration. The two examples given in the fifth report (Figure A2(b)) show no effect on the maximum concentration and a small increase in the far field due to the limited mixing depth. Similar effects would be predicted for sources up to about 10 km from the coast.

An estimate is also given in the fifth report of the effect on dispersion from a source above the internal boundary layer (Figure A2(a)). In comparison with the same source inland, it is shown that the maximum ground-level concentration is reduced and its distance from the source increased, whereas concentrations in the far field are shown to be increased because of the limited mixing depth. The evaluation refers to a 30 minute emission but the conclusions are also applicable to emissions of longer duration. For an emission of a few minutes, even with no mixing in the external flow, effects would not be large, since the virtual source would be located at the point where the internal boundary layer height equals the source height. Thus, behaviour would be as described above for a source in the internal layer, the concentration field being displaced the appropriate distance down wind.

Other models proposed for coastal effects sometimes include the assumption that material is immediately brought to ground once it crosses the interface between the stable and unstable layers. Such models would predict that peak concentration at a coastal site will be greater than that at an inland site for the same conditions. A prediction of the Group's model is compared with that for the Lyons and Cole(19) model in Figure 2. The figure also illustrates the effect of reasonable changes in the assumed depth of the internal boundary layer.

6. MODEL VALIDATION STUDIES

The Group has not undertaken any field studies to test as a whole the models proposed in its reports. Many aspects of the models have at some stage been compared with experiments and the models' predictions have also been compared with those of other models. Many of these studies have been reported in the relevant sections of the Group's reports. A considerable number of attempts to test dispersion models have been reported in the literature and conclusions on the validity of the Group's models can be drawn from these studies, some of which are considered below.

A US workshop has considered the accuracy with which the Gaussian plume model can predict atmospheric dispersion(20). The conclusions of the workshop can be summarised to give the likely range of the ratio of predicted to observed concentration for defined conditions as

- highly instrumented flat terrains; ground-level centre-line concentration within 10 km of a low-level source; steady atmospheric conditions	0.8 - 1.2
- specific hour and receptor point, flat terrain, steady meteorological conditions, within 10 km of the release point	0.1 - 10
- long-term average concentration at a specific point, flat terrain, within 10 km of the release point	0.5 - 2
- monthly and seasonal averages, flat terrain, 10 - 100 km down wind	0.25 - 4

A number of comments should be made about the ranges quoted. The first entry considers the ability to predict the concentration on the plume centre line, with no allowance for ability to locate the direction of the centre-line. The estimate assumes the availability of a considerable amount of local meteorological data, such as wind speed and direction at two heights and measurements of the standard deviation of the horizontal and vertical wind directions, and possibly the use of site-specific dispersion data to relate plume size to the values of the meteorological parameters. If these data are not available, then the ratio of the predicted to observed concentration would be larger, by a factor of about two or three. This Group does not consider that any model would always predict centre-line concentrations within 20% even in ideal conditions and with the site-specific data indicated above. The increased uncertainty in predicting concentration at a point stems from uncertainty in the wind direction and the sensitivity of the term exp $(-y^2/2\sigma_y^2)$ to small changes in

σ_y near the edge of the plume, and to the accuracy with which wind direction is known.

Little and Miller(21) have summarised a number of experiments in which Gaussian plume models have been tested. They present results both for ensemble averages and for the range of the ratio of observed to predicted concentration encompassing specified fractions of the results. Table 5 summarises some of their conclusions for situations where the Gaussian model is applicable. They also give results of validation studies for situations where the Gaussian model is less likely to be applicable, such as complex terrain and low wind speeds.

Vanderborght et al(22) have compared concentrations and depositions measured within 4 km of a metallurgical plant with the predictions of a Gaussian model including allowance for wet and dry deposition and plume rise. The concentration was averaged over periods of 21 h and the deposition rate over periods of 28 days. Comparisons of measured and predicted air concentrations were carried out for both the cumulative frequencies of concentration and the concentrations at specific times. The mean concentration and peak 21 h concentration were predicted to within 40% by the model used. The comparison shows a larger difference between measured and predicted concentrations at a given time, however, the great majority of concentrations were predicted within a factor of five.

Kretzschmar et al(23) have carried out a series of releases of SF_6 over an agricultural area near Mol in Belgium. The observed values of σ_y and σ_z were compared with the predictions of a number of dispersion models, including that recommended by Group, while observed concentrations were only compared with the predictions of the model developed at Mol. The travel distance covered by the data was from about 600 m to about 7 km. The results of the comparison, expressed as a relative difference between model and observation, are shown in Table 6. The prediction of σ_y obtained from the Working Group model is, on average, 20% greater than that observed. This discrepancy is comparable to that obtained for the SCK model which is based on observations made at Mol and in the centre of the range from other models. The prediction of σ_z is, on average, about 20% less than that observed, which is not as good as that for the SCK model but better than the prediction of any of the other models considered. The ratios of predicted to measured concentration for the SCK model range from 0.3 to 2.9 with a mean value of 1.02 ± 0.65.

Draxler(24) has compared the predictions of a simple and an improved Gaussian model with observed concentrations of ^{85}Kr discharged from the Savannah River Plant. Concentrations were measured at 13 points between 30 and 150 km from the source, distances greater than those at which a simple Gaussian model should be applied. Some of his results are shown in Figures 3 and 4, taken from his paper. Figure 3 shows the probability of predicting the weekly average concentration within a given factor; about 60% of the values predicted by the improved model are within a factor of five of the observed ones. Figure 4 shows that the error of the prediction decreases with increasing averaging time. The improvements which Draxler made to the standard Gaussian model were an improved treatment of calm conditions, the use of wind speed at release height rather than 10 m and an allowance for changes of atmospheric stability during plume travel. These aspects of his model are included, at least on average, in the Group's model for long range dispersion from a continuous release. Therefore, Draxler's results indicate the likely performance of the Group's model at distances between 30 and 150 km from the source. They also give an indication of the likely performance of the Group's model at shorter range, where the stability category has not changed during the travel of the plume.

Moore(25) describes a Gaussian model for calculating ground-level concentrations due to power station emissions. About 3000 sets of hourly averaged observations of ground-level concentration for heat emissions in the range from 20 to 120 MW, from 100 and 150 m stacks, were used to test the model. The data were grouped into three stability bands, nine wind speed bands and two source-height bands. The ratio of the ensemble mean observed to the calculated concentration at the point of maximum concentration lay between 0.9 and 1.1, and the standard deviation of calculated hourly concentrations about the mean was about 60% of the ensemble mean. Larger scatter was observed in convective conditions, with smaller scatter in near neutral conditions. The effects of errors in the evaluation of plume rise were analysed and shown to contribute about 40% of the total variance, implying that the standard deviation of the calculated concentrations due to the dispersion model was about 45% of the ensemble mean (see Table C1 of the Group's first report for a more detailed presentation). For elevated emissions, prediction of the maximum ground-level concentration is the most straightforward modelling task and the above accuracy will not be attained for other receptor locations. As Moore's model is more refined than that proposed by the Group, it is to be expected that the performance of the latter when calculating the behaviour of elevated emissions will be slightly inferior.

Whereas Moore assessed the performance of his dispersion model against a full set of hourly averaged concentration data, Barker(26) tested the Working Group's models against the ensemble averaged data, categorised according to wind speed, stability and source height. Maximum ground-level concentrations were predicted to within 30% on average, providing use of the model was restricted to effective source heights below 400 m in unstable, 300 m in neutral, and 200 m in stable conditions. Consistent overprediction was noted in unstable conditions, by 20 to 30% on average, and underprediction in windy neutral conditions by 30 to 40% on average. The position of the maximum ground-level concentration was predicted to within 50% on average, given the height restrictions mentioned above. The situation was least satisfactory for stable conditions as calculated values were consistently greater than observed. Moore(8) has shown that prediction of the position of maximum ground-level concentration should take into account plume spread generated through plume rise in order to minimise errors. This is also recommended in the Group's fifth report, but was not included in the above work. Moore and Lee(27) have also noted that it is important to include intermittent escape from the boundary layer in models of dispersion from sources of large effective height.

Barker(28) has also examined the performance of the model proposed for continuous emissions from a building. Ground-level dilution factors for ^{35}S emissions from roof-level sources at two AGR power stations were derived from measurements of activity in milk and grass samples. The experiments covered a period of nine months in one case and eleven in the other, and fetches between about 100 m and 6 km. Source strength, wind rose and stability category frequency data were well defined. Uncertainty in transfer factors implied about a 50% range on the experimental results. Predictions of the dilution factor were, on average, within 30% of the best estimates from the measurement, though in some cases differences of a factor of two were obtained, particularly at short range, where the model tended to overpredict.

Fackrell(15) and Foster and Robins(16) have compared predictions of the "virtual source model" for building effects with full scale data from the EOCR reactor site (Idaho Falls) and Oldbury Power Station. At Oldbury, only near-neutral stability cases were studied. Concentration fields, due to fifteen minute releases at roof, mid-height, and ground level, were measured over distances between about two and ten building heights down wind. Close to the building the ratio of measured to predicted peak ground-level concentration ranged from 0.6 to 1.2, becoming 0.3 to 0.9 at the farthest downstream positions. Plume dimensions were not particularly well predicted, however, and it was suggested that the inherent simplicity of the model probably excluded adequate prediction of off-centre-line concentrations and plume dimensions. Unlike Oldbury, the EOCR site experiences a continental climate. Experiments were undertaken in stable, neutral and unstable conditions, ground-level concentrations being measured between about two and sixty building heights down wind for passive emissions from ground and roof level. There was considerable scatter in the observations, particularly in stable conditions when a factor of 100 range or more was observed, at fixed distances down wind. This resulted from a number of factors, the major one being the great variability of the lateral turbulence under conditions of nominally similar lapse rate. The model predicted the upper bounds of the observations within a factor of two or three, except for three cases in unstable conditions when the degree of underprediction was greater. The Group's first report includes the option of calculating lateral spread from measured statistics of the lateral turbulence component. Using this approach would reduce some of the differences between the predictions and the observations, though the analysis has not been undertaken.

7. SUMMARY AND CONCLUSIONS

This report has examined the reasons for differences between observed concentrations and depositions and those predicted by atmospheric dispersion models. The range of uncertainty inherent in a model prediction has also been considered.

The uncertainty in model predictions and the discrepancies between observed and predicted concentrations stem from a number of features, such as the random nature of atmospheric dispersion processes, idealisations incorporated in models and the difficulties of choosing representative values for the many parameters considered. Each of these aspects has been considered in this report. The identification of idealisations in the models has led to a discussion on the conditions where the Group's models apply. Dispersion models require the user to select a best-estimate value for each parameter and the likely range for each parameter value is considered in this report. The report also describes some of the validation studies which have been undertaken for dispersion models similar to those selected by the Group. While it has not been possible to give a firm quantitative statement of the likely accuracy of model predictions, more qualitative statements of the models' reliability have been given based on these validation studies and the identification of the main sources of uncertainty in the models.

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Table 1

Criteria for neglecting orographic effects

In neutral and unstable conditions

- the gradient of the surrounding terrain should be less than about 1 in 10

- for a ridge upwind of the source
  either $h > 1.5\ H$
  or $x > 20\ H$ in neutral conditions
  $x > 10\ H$ in very unstable conditions

- for an islated hill upwind of the source
  either $h > 1.5\ H$
  or $x > 7\ H$

- for a hill or ridge downwind of the source
  either $h > H + \sigma_z\ (x)$
  or $\sigma_z\ (x) > H$

In stable conditions

- the gradient of the surrounding terrain should be less than about 1 in 100.

- for an obstacle upwind of the source
  either $h > H$
  or $x > 40\ H$ in slightly stable conditions
  $x > 100\ H$ in very stable conditions

- for an obstacle downwind of the source
  either $h > H + \sigma_z\ (x)$
  or $\sigma_z\ (x) > H$

Notes:

The criteria are based on a change of 30% in the wind speed between flat and complex terrain.

The 10 m wind speed must be at least 1 m s^{-1}.

h = the release height.

H = the obstacle height.

x = the distance between obstacle and source.

$\sigma_z\ (x)$ = the vertical plume standard deviation.

Table 2

The range of roughness length causing a change in wind speed at 10 m of 30% or less

Initial roughness length m	Range of roughness length m
0.01	≤ 0.2
0.1	≤ 0.5
1	0.5 - 2.0
3	2 - 5

Note:

1. The values are for neutral stability. The variation of wind speed at 10 m with roughness length is similar in unstable conditions and is less in stable conditions. In stable conditions a change in stability category, associated with the roughness change, could result in larger wind speed variations.

Table 3

The probability that a stability category persists for given times

Duration (hours)	Probability of category persisting						
	A	B	C	D	E	F	G
1	$5.0\ 10^{-1}$	$6.3\ 10^{-1}$	$6.4\ 10^{-1}$	$8.8\ 10^{-1}$	$4.2\ 10^{-1}$	$6.1\ 10^{-1}$	$6.0\ 10^{-1}$
2	$2.6\ 10^{-1}$	$4.0\ 10^{-1}$	$4.1\ 10^{-1}$	$7.9\ 10^{-1}$	$2.1\ 10^{-1}$	$3.9\ 10^{-1}$	$3.8\ 10^{-1}$
3	$1.4\ 10^{-1}$	$2.5\ 10^{-1}$	$2.6\ 10^{-1}$	$7.1\ 10^{-1}$	$1.0\ 10^{-1}$	$2.5\ 10^{-1}$	$2.5\ 10^{-1}$
4	$7.1\ 10^{-2}$	$1.5\ 10^{-1}$	$1.6\ 10^{-1}$	$6.6\ 10^{-1}$	$5.4\ 10^{-2}$	$1.6\ 10^{-1}$	$1.7\ 10^{-1}$
5	$3.4\ 10^{-2}$	$8.9\ 10^{-2}$	$1.0\ 10^{-1}$	$6.1\ 10^{-1}$	$2.9\ 10^{-2}$	$1.0\ 10^{-1}$	$1.2\ 10^{-1}$
6	$1.4\ 10^{-2}$	$4.8\ 10^{-2}$	$6.1\ 10^{-2}$	$5.7\ 10^{-1}$	$1.6\ 10^{-2}$	$6.1\ 10^{-2}$	$8.1\ 10^{-2}$
9	-	$2.8\ 10^{-3}$	$9.0\ 10^{-3}$	$4.8\ 10^{-1}$	$2.5\ 10^{-3}$	$1.1\ 10^{-2}$	$2.3\ 10^{-2}$
12	-	-	$2.7\ 10^{-4}$	$4.1\ 10^{-1}$	$1.3\ 10^{-4}$	$2.6\ 10^{-3}$	$3.6\ 10^{-3}$
15	-	-	-	$3.6\ 10^{-1}$	-	$2.8\ 10^{-4}$	-
18	-	-	-	$3.1\ 10^{-1}$	-	-	-
24	-	-	-	$2.4\ 10^{-1}$	-	-	-

"-" indicates that the data set used to derive this table contained no instance in which the indicated category persisted for the time period.

Table 4

The range of uncertainty for each parameter value

Parameter	Uncertainty
Stability	±1 Pasquill category over a region (10's km)
Wind speed	(a) ±2 m s^{-1} over a region in average conditions (b) Ranges for a given stability category as given in Figure 2 of the Group's first report
Wind direction	±20° over a region
Mixing layer depth	±50% range
Vertical plume spread (σ_z)	Within the range of values midway between adjacent stability categories
Lateral plume spread (σ_y)	(a) Turbulence component as for vertical spread (b) Wind direction component ±20% for ensemble average
Deposition velocity	Generally order of magnitude, except in well-defined applications
Washout coefficient	(a) A factor in the range 5 to 10 for a rainfall rate of about 1 mm h^{-1} (b) Increasing with rainfall rate

Table 5

Summary of some validation results for Gaussian plume models[1]

Conditions	Range of the ratio $\frac{\text{Predicted concentration}}{\text{Observed concentration}}$
Annual average concentrations from point and area sources, for a site in Tennessee	0.5 - 2.0
Short-term ground-level releases of fluorescein in stable conditions at Hanford, Washington	0.2 - 5.0 72% of samples
Short-term SF_6 releases from a 36 m stack, categories B to F, for a site at Denver, Colorado	0.33 - 3.0 89% of samples 0.1 - 10 100% of samples

Note:

1. Extracted from Little and Miller(21).

Table 6

A comparison of observed values of plume size with those predicted by a number of models[1]

Model	Results for σ_y		Results for σ_z	
	Average of relative difference[2] (%)	Absolute standard deviation[2]	Average of relative difference[2] (%)	Absolute standard deviation[2]
SCK	22	25	- 7.1	59
Pasquill	7.9	41	- 45	83
Pasquill[3]	2.2	34	- 43	80
Pasquill[4]	-5.3	30	- 66	53
Briggs open	15	38	- 34	82
Briggs rural	59	37	69	62
Turner	-9.2	30	- 76	66
UK working group	20	37	- 23	70
Klug	-13	51	- 66	96
Vogt[5]	44	32	61	57
Vogt[6]	61	40	50	38
Doury	54	49	- 84	40

Notes:

1. Taken from Kretzschmar et al(23).
2. Relative difference (r) $= \dfrac{\sigma \text{ model} - \sigma \text{ observed}}{0.5\,(\sigma \text{ model} + \sigma \text{ observed})} \times 100.$

   Average of relative difference $(\bar{r}) = \frac{1}{n} \sum_i r_i$

   Standard deviation $= \left[\frac{1}{n-1} \sum_i (\bar{r} - r_i)^2\right]^{\frac{1}{2}}$

3. With stability determined from the vertical temperature gradient, as recommended by USNRC.
4. With stability determined from the vertical temperature gradient and wind speed.
5. With stability determined from solar elevation, cloud cover and wind speeed.
6. With stability determined from wind speed and vertical temperature gradient.

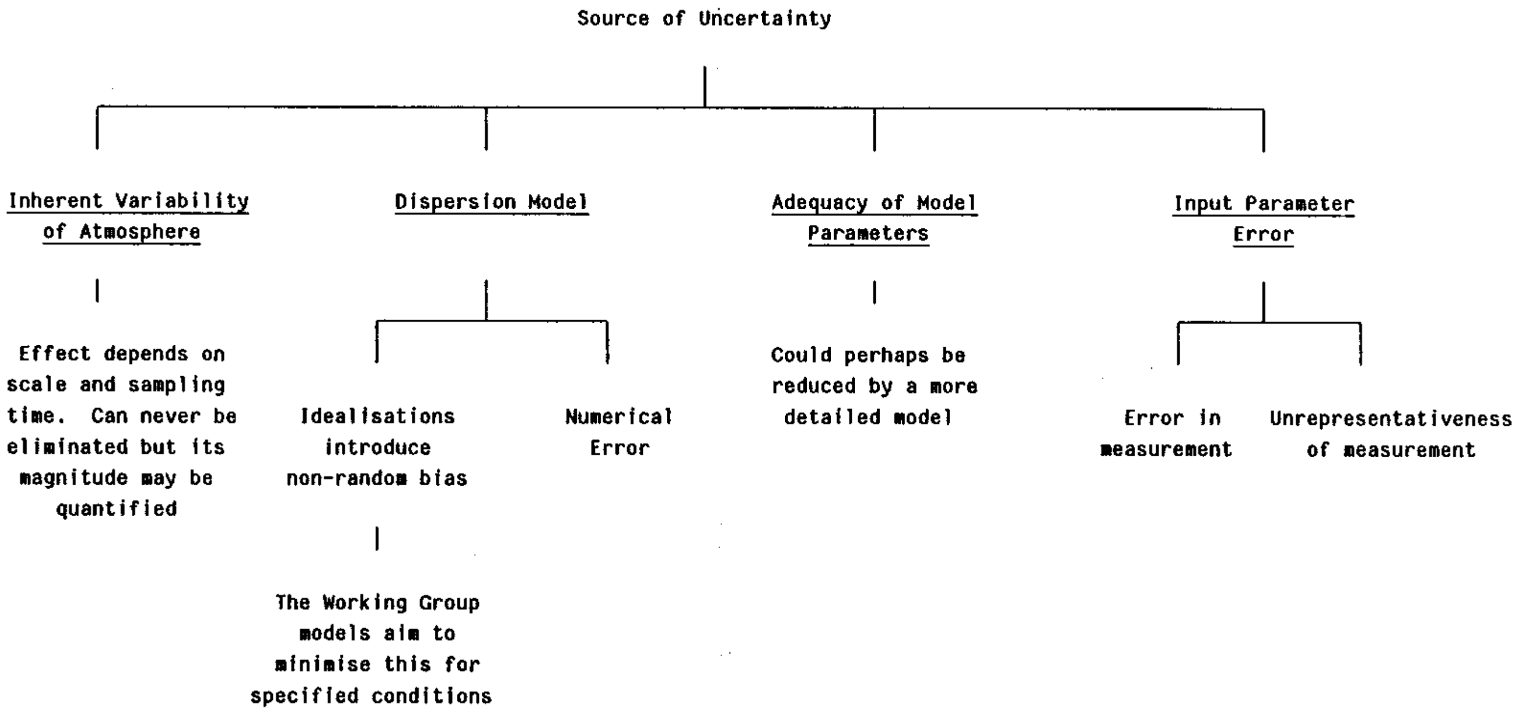


Figure 1 Sources of uncertainty in dispersion modelling

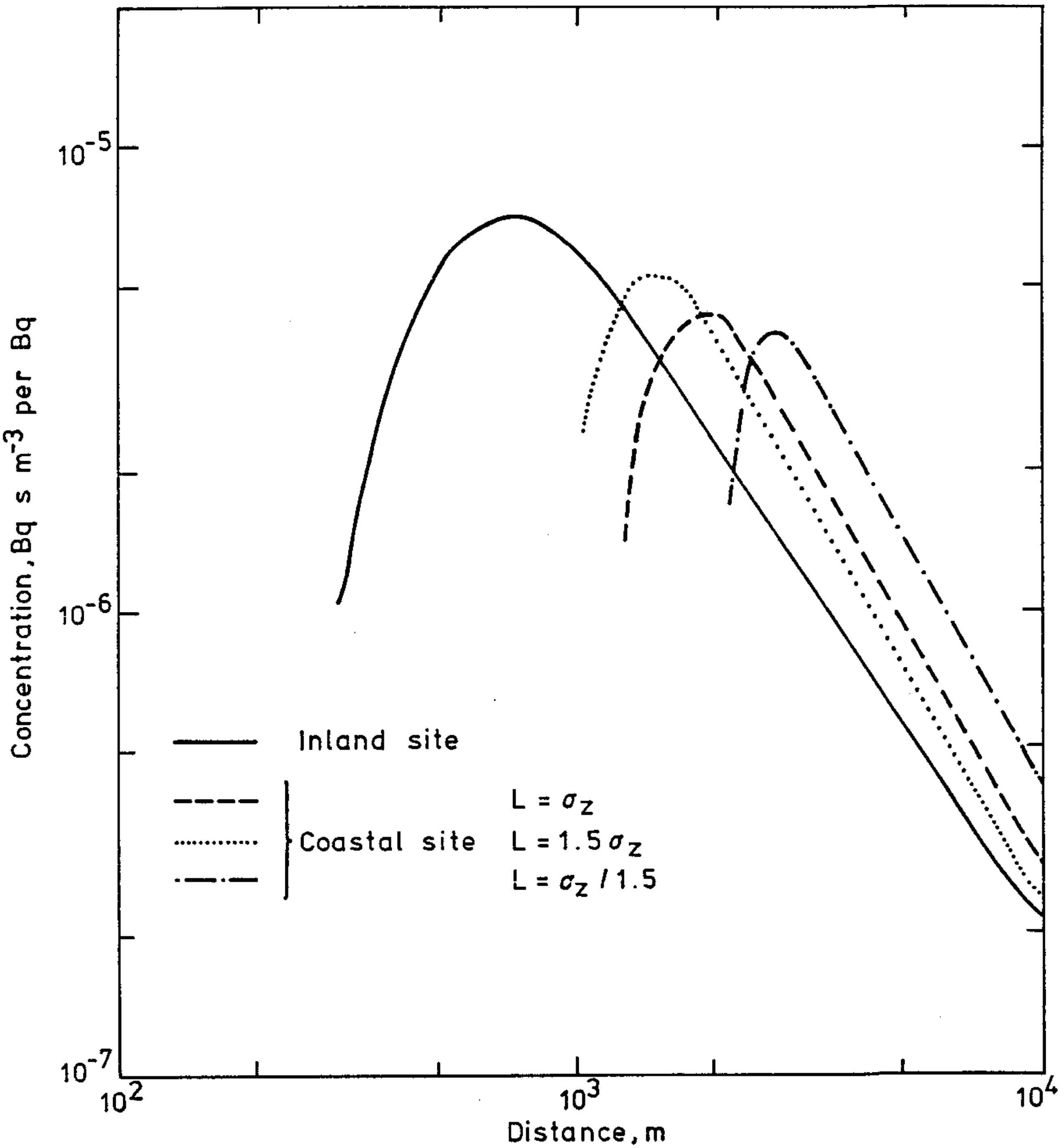


Figure 2a A comparison of the concentrations predicted by the UK Working Group coastal model with those for an inland site

(Note: L is internal boundary layer depth)

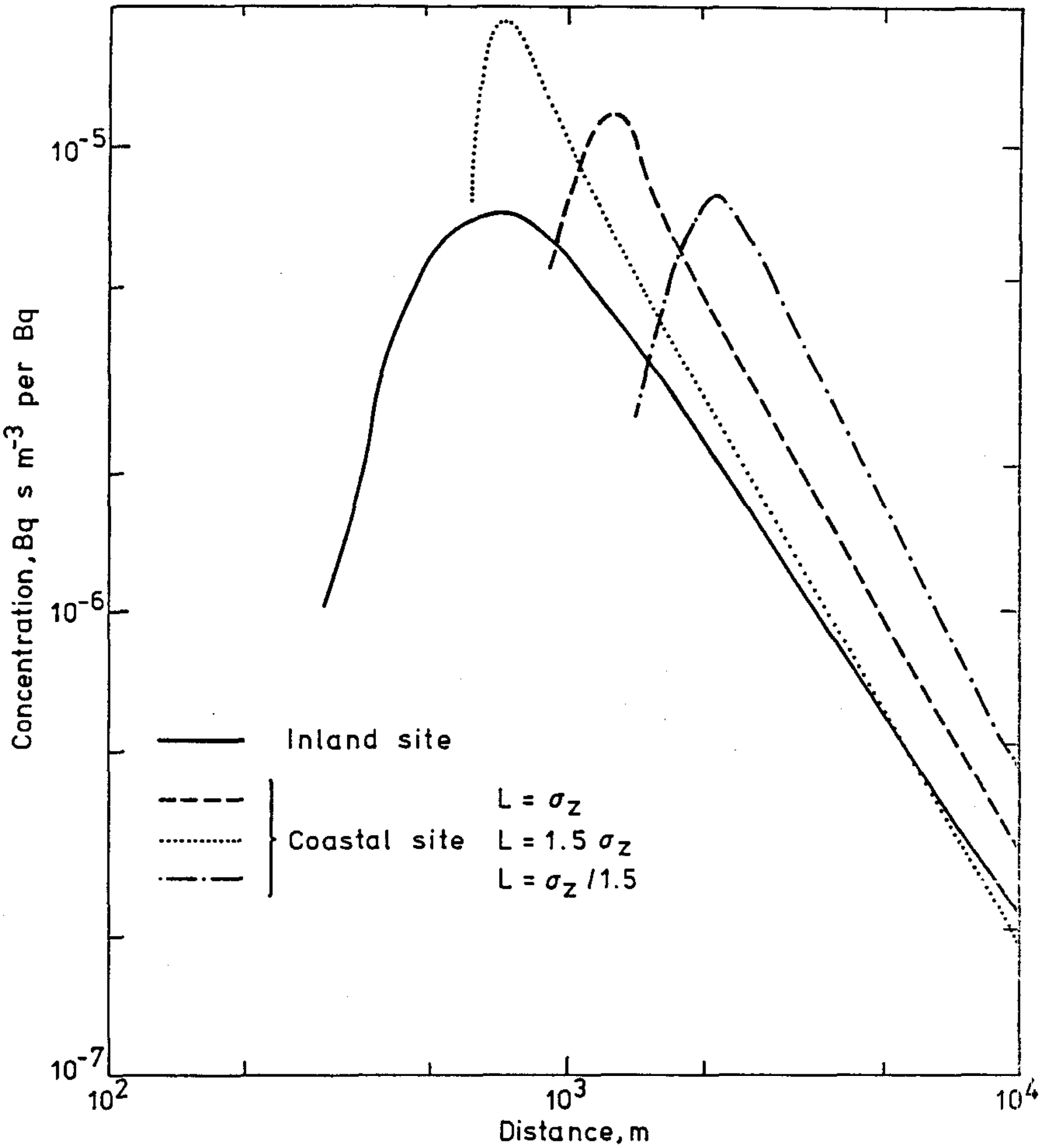


Figure 2b A comparison of the concentrations predicted by the Lyons and Cole coastal model with those for an inland site

(Note: L is internal boundary layer depth)

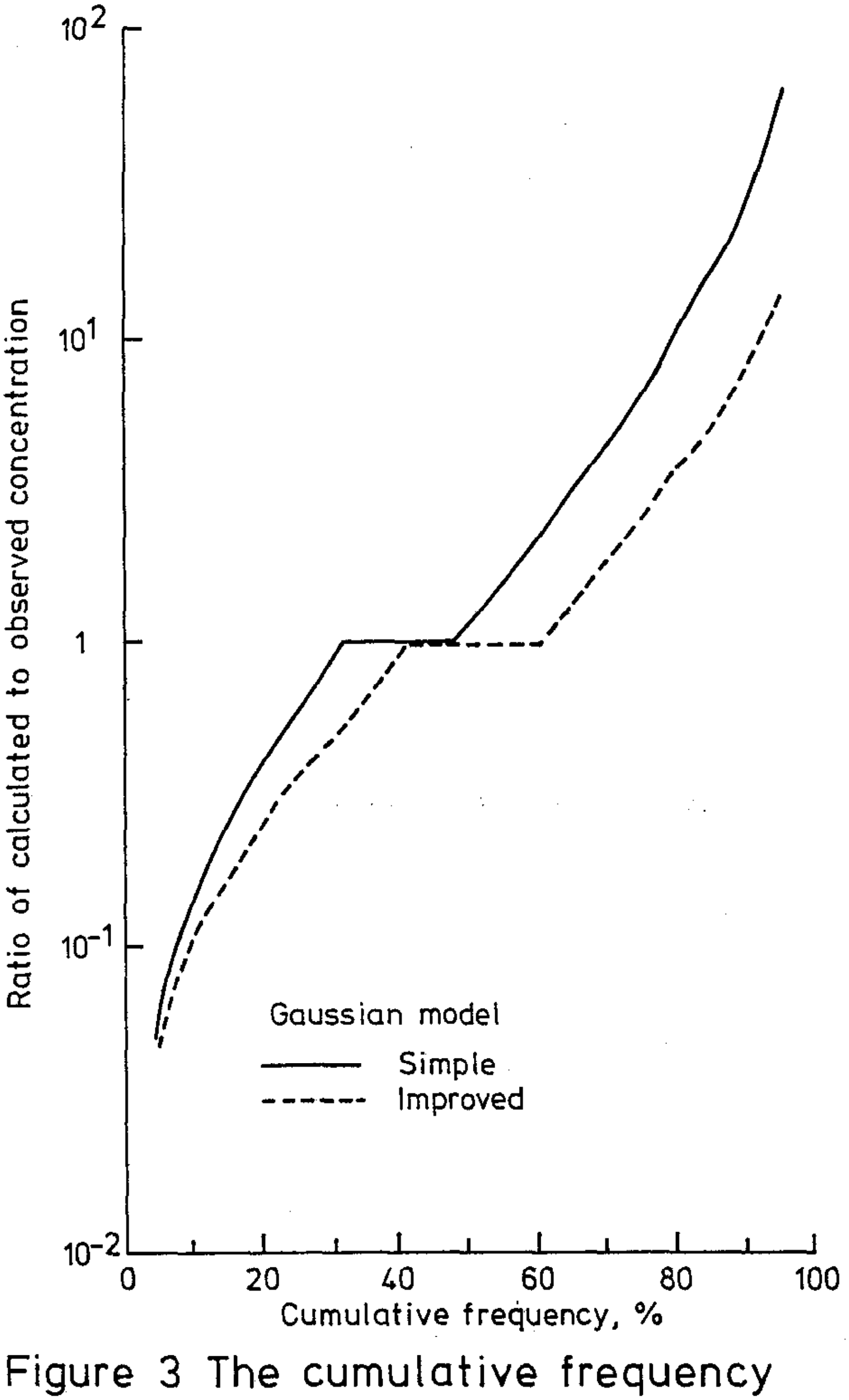


Figure 3 The cumulative frequency distribution of the ratio of calculated to observed concentrations, using a simple and an improved Gaussian model (Based on Draxler(24))

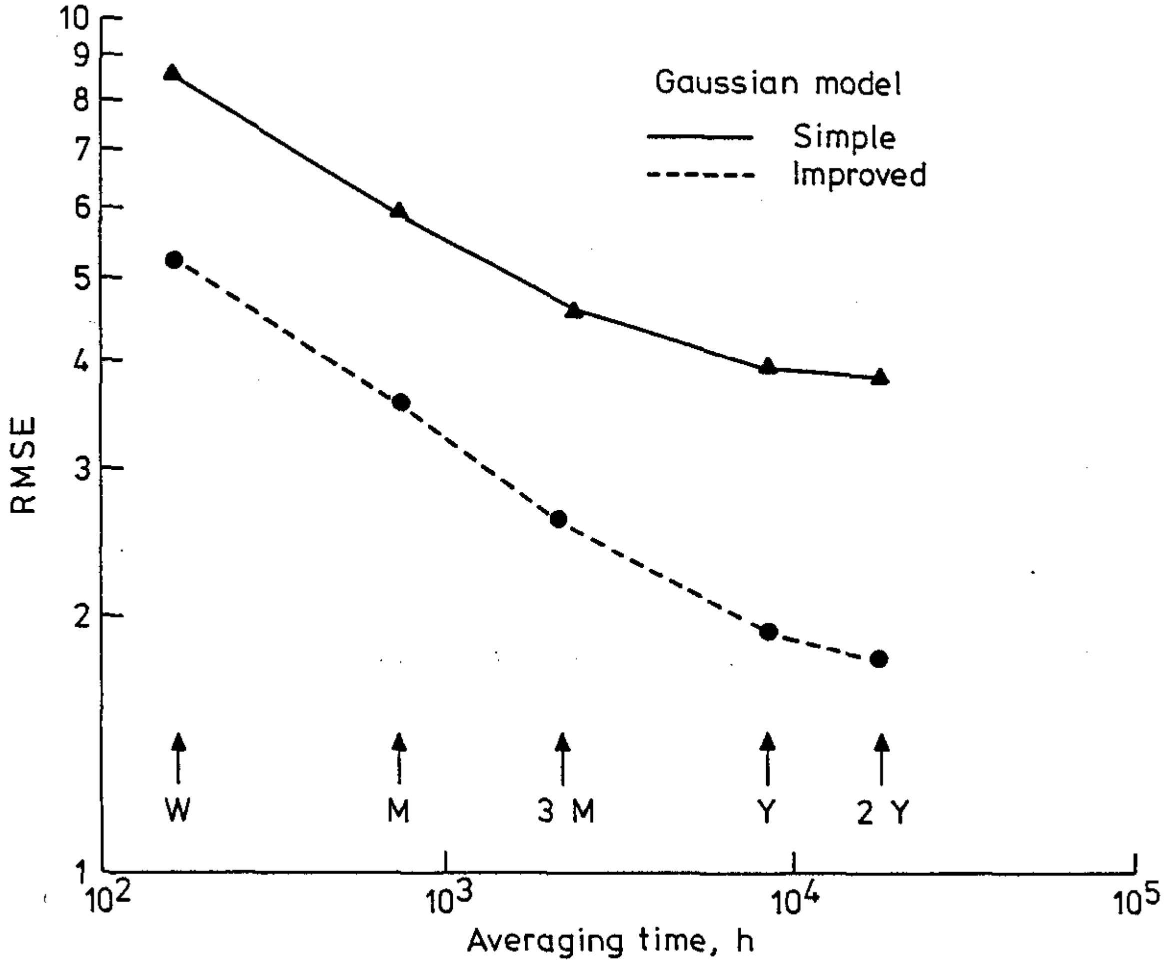
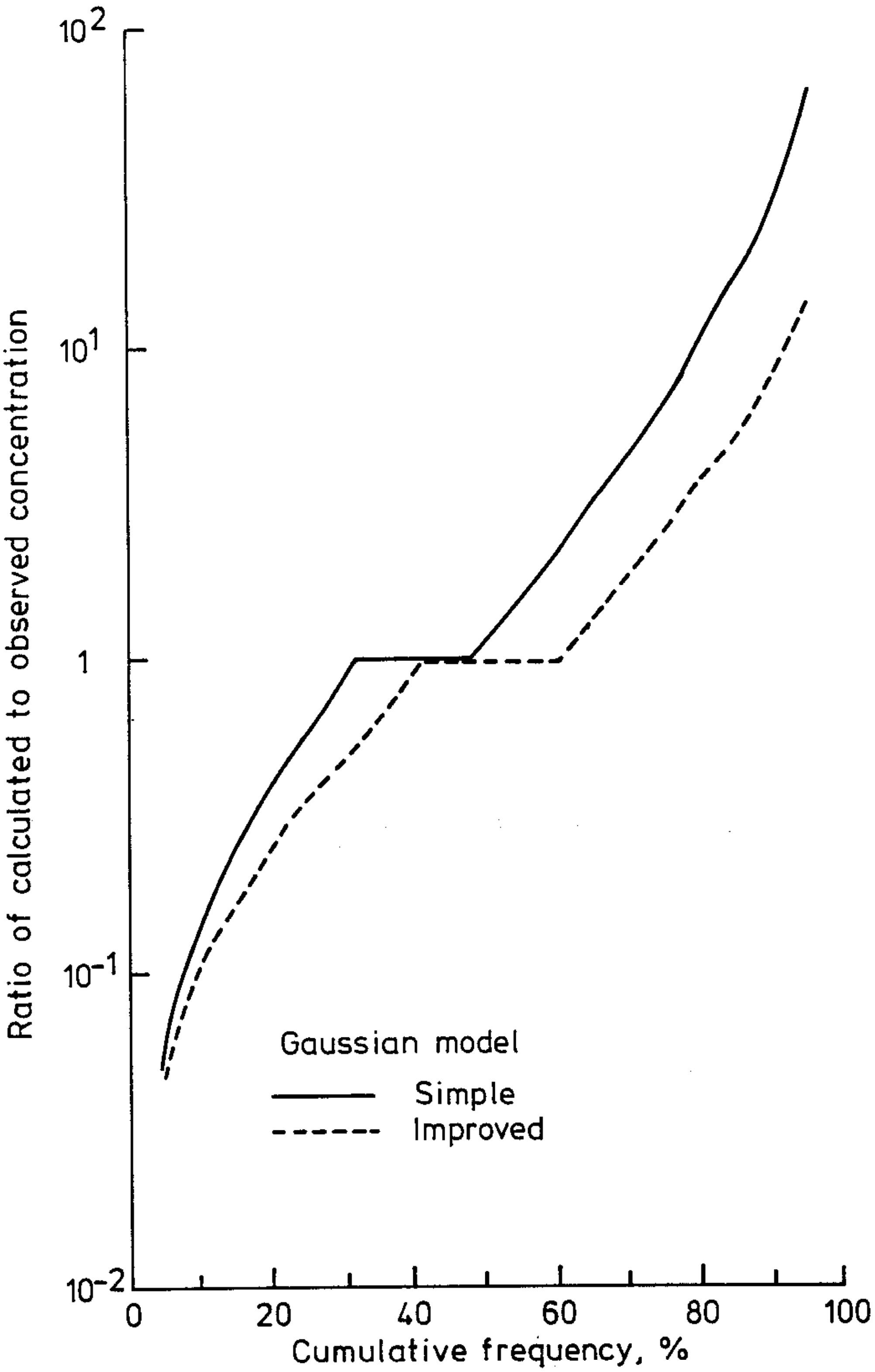


Figure 4 Comparison of the prediction of a simple and an improved Gaussian model with observed concentration

(Note: RMSE = $\exp\left[\sum\frac{1}{n}(\ln C_c/C_o)\right]^{1/2}$ where C_c is the prediction and C_o is the observed concentration)



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