An Inter-comparison of the AERMOD, ADMS and ISC Dispersion Models for Regulatory Applications

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EXECUTIVE SUMMARY

The present study is concerned with relationships between air dispersion models currently in use for authorisation applications to the Environment Agency. These are mainly the older Pasquill/Gifford types of model (represented here by the USEPA ISCST3 model, called ISC in the report) and the 'advanced' models, the USEPA AERMOD model and the CERC's UKADMS model, called ADMS in the report. The two advanced models have been developed from the research base of more recent years, follow generally similar principles and calculate dispersion from a greater number of input parameters. They rely particularly on estimates of the boundary layer height and the Monin-Obukhov length scale as an atmospheric stability parameter. The ADMS model has been in use in the UK for over six years and has become the dominant model for authorisation studies presented to the Agency. However, AERMOD has become readily available over the last 18 months and the Agency expects to receive a growing number of authorisation applications using this model. It therefore required guidance on the relationships between the two models and on their performance in typical authorisation situations. In particular, it wished to know what differences in calculated pollutant concentrations might arise between the models and what other features of their behaviour might affect the results of authorisation studies. This is not the same as a validation study, in which the accuracy of models is assessed by comparing them with field measurements.

The present study had two main aims. Firstly, to lay down a test protocol that could be used for the present and future intercomparisons, so that a historical perspective of the differences between models and different versions of models could be developed. Secondly, to carry out the first such intercomparison for the Agency using the two advanced dispersion models, ADMS and AERMOD.

The report lays down a suitable protocol for model intercomparison which tests all the main features of models used in regulatory practice with a minimum number of calculations. These include calculations in single weather conditions, to show the response of the models to specific meteorological circumstances, and annual calculations (using hourly weather data for a single year) of the form that are normally used in regulatory work. The test cases used two stack discharge heights, of 40m and 150m, with and without discharge buoyancy, and covered the following aspects of dispersion:

Basic rates of dispersion in neutral, stable and unstable boundary layers
Plume Rise
Buoyant plume interaction with the top of the boundary layer
Building entrainment
Varying surface roughness
Terrain
Meteorological data input

The terrain cases used a modified form of the Porton Down test range terrain.

The test protocol generally served its purpose well and represents a sound basis for future work of this type. The study has found significant differences in calculated concentrations between the three models from a regulatory viewpoint. A broad indication of the differences between the models can be obtained from a simple count of the ratios of maximum concentrations in the various Tables throughout the report. In these, of the ratios of ADMS/AERMOD maximum concentrations, about 28% of the ADMS/AERMOD ratios exceeded a factor of two, of which 15% were high (>2) and 13 % low (<0.5). Of the ISC/AERMOD ratios 38% exceeded a factor of two, of which 35% were high (>2) and 3%

low (<0.5). The majority of the differences exceeded 20%. A simple summary of the results would be that, overall, ADMS produced maximum concentrations that were a little higher than AERMOD and that ISC produced maximum concentrations that were more generally higher than AERMOD and, by inference, than ADMS. However, in searching for consistent differences in behaviour between the three models, one of the conclusions of the study was that there did not seem to be many. Even the quite specific individual aspects of dispersion examined here exhibited quite variable relationships between the models. It was not, therefore practicable to offer reliable blanket guidance on the differences between the models. Guidance from the intercomparison is therefore best achieved by examining those aspects closest to the specific problem in hand.

Considering the relative similarity in the structure of the basic dispersion calculations in the advanced models, the large differences in predicted concentration between them at times seemed surprising. A critical feature of these differences may lie in their meteorological pre-processors, which take the raw meteorological site data and convert it to the boundary layer parameters needed for the dispersion calculation. These produced markedly different estimates of boundary layer depth and Monin-Obukhov length scale (the two critical parameters for the advanced models). The advanced models appeared to be quite sensitive to the values used and in a brief test in which the two pre-processor outputs were input to one of the models for an annual calculation, significant changes in the calculated concentrations resulted. This conclusion also carries important implications over the quality and use of raw meteorological data used by the models.

It appears that the advanced models and their meteorological pre-processors are still in a state of scientific development which has not yet converged to a consensus view of how they should behave. This situation means that ongoing modifications to the models (for example between successive versions of the same model) can produce significant changes in both their absolute and relative performance. The use of advanced models for regulatory purposes remains necessary as these models offer improved versatility and performance in many aspects of dispersion modelling, but some caution and understanding is needed in their use. The further development of these dispersion models, and of their meteorological pre-processors, should be encouraged by an open attitude to their contents and working. This is somewhat lacking at present with regard to the ADMS model.

We make the following recommendations for further work and future Agency policy in this area:

1) That the Agency should accept the need to deal with dispersion calculations using a variety of models. The ADMS and AERMOD 'advanced' models investigated here are likely to be the main contenders for such work at present and we can find no reason from the present study to specifically exclude either of them from such work. There remains a usefulness for the older, Pasquill/Gifford type of model (mainly the ISC and R91 models in the UK) for rapid screening studies and other work. They are fast, easily understood and retain an historical link with earlier regulatory studies. However, the 'advanced' models have in principle a better capacity for dealing with more complex meteorological situations and should be the preferred models for regulatory studies, particularly in complex or contentious situations.

2) That it be recognised that atmospheric dispersion models are imperfect and, for the 'advanced' models especially, still subject to scientific uncertainty and further development. In particular, different models and versions of models may produce markedly different results in regulatory studies. The Agency will need to understand these

differences, the ways in which they arise and to take account of the uncertainties associated with this type of calculation in its regulatory decisions.

3) That as part of this process, the Agency should use the test protocol outlined here (possibly with some refinement) as the basis for a test procedure examining all existing and new air dispersion models, or new versions of models, which are likely to be used by the Agency or in applications for authorisation. It is important that the test protocol remains stable over a long period so that differences between models and versions of models can be assessed historically for their effects on regulatory decisions. This follows current good practice, by the USEPA for example, who do not permit the use of new models or model versions without such testing.
4) That this process of model assessment be carried out by disinterested parties, independent of either the developers or distributors of the models, or of the Agency or other regulatory authorities. Initiating this process should be the responsibility of the Agency as the need arises. The results of such studies should be open and distributed freely to any interested parties. It would be preferable if they were published in the peer-reviewed scientific literature.
5) That the Agency should encourage an open attitude to the use and development of models, so that their effective scientific development (which is an essential need) should be unhindered and that all interested parties should have a clear understanding of their performance.
6) That the Agency itself should continue to fund the investigation and development of dispersion models where it can be seen to enhance its regulatory practice. In doing so, it should ensure that such work is openly accessible to the research and regulatory communities. In particular, the rights to any developed computer code funded by the Agency should remain with the Agency and be publicly available, as with the ISC, AERMOD and other codes generated by the USEPA.
7) That the Agency should base its future policy with regard to the use and development of dispersion models on the Royal Meteorological Society's 1995 Guidelines.

Keywords:
Air pollution; dispersion modelling; model comparison; model evaluation; impact assessments; ISC; R91; AERMOD; ADMS.

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Notation

c_p Specific heat at constant pressure (1012 J K^{-1} kg^{-1}).

f Coriolis parameter (1.1x10^{-4} s^{-1} at 53°N).

h Maximum height of terrain (m).

H Boundary layer depth (m).

k Von Karman's constant (0.4).

K Normalised concentration (m^{-2}).

L_{mo} Monin-Obukhov length scale (m).

N Brunt-Vaisala boundary layer frequency.

Q Pollutant emission rate (g s^{-1})

q_0 Surface sensible heat flux (W m^{-2}).

T Absolute temperature (K).

u_* Friction velocity (m s^{-1}).

u Wind speed (m s^{-1}).

w Vertical wind component over terrain (m s^{-1}).

z_i Height of elevated inversion (m).

z_0 Aerodynamic roughness height (also called surface roughness) (m).

ρ Ambient density (kg m^{-3}).

τ_0 Surface shear stress (Pa).

χ Pollutant concentration (g m^{-3}).

Δu, Δw Changes in u and w due to terrain.

1 INTRODUCTION

The use of air dispersion modelling is a crucial feature of the Environment Agency's IPC procedures in assessing the exposure of the environment to air pollutants from plant under its regulatory control. It is now standard practice for air dispersion studies to be submitted for all applications for authorisation where there are significant polluting discharges to the atmosphere. There is at present no formally standardised way of doing this and the Agency does not specify the use of particular models or techniques. A variety of dispersion models, different versions of models and approaches to modelling may therefore be used in applications for authorisation.

For these reasons, the way in which models are used and any differences between them in calculating ambient concentrations are of great importance in regulatory practice. This is especially so since such differences can be very large in a regulatory sense, though within the bounds that might be considered acceptable scientifically. It is difficult to predict from first principles what effects these differences between the models might have on their respective dispersion calculations, so that a direct inter-comparison by calculating similar dispersion cases is the required approach. The practical differences in using models are also important in IPC work as large numbers of calculations may have to be made, so reliability and ease of utilisation of a model then become important.

Despite this need there are few systematic model inter-comparison studies which would allow the Agency to take an informed stance on their use, backed up by adequate technical information. Most inter-comparisons are with field data, for validation purposes, carried out by model developers. Only the occasional use of more than one model in such studies that has provided most of the information on the differences between models. Previous work of this sort has been reviewed, by Hall et al(1999c) as a precursor to the present study; the review also includes a discussion of the philosophical and regulatory background. A further discussion of this matter and an example of differences in dispersion calculations due to using two different versions of the same model and two sources of meteorological data can be found in Hall and Spanton (1999a) and in Hall et al (1999b). The background to these matters is not therefore considered in any more detail here.

We consider that as a matter of principle greater impartial attention should be given to the performance of dispersion models and the relative behaviour of different models, regardless of any issue of a regulatory nature. This is discussed at length by the Royal Meteorological Society's (R Met Soc(1995)) policy statement on guidelines for atmospheric dispersion modelling, to which one of the Agency's predecessor organisations (HMIP) was a contributor. In this document the Society stresses the importance both of the ways in which models are used and of the critical need for independent verification and audit. However, the number of openly published, disinterested studies satisfying the Royal Meteorological Society's criteria is small.

At present the short range air dispersion model mainly used in the UK for IPC authorisation purposes is the UKADMS model (Carruthers et al(1994), currently version 3, called ADMS here). This is a 'new generation' model. Its performance in relation to older models, the USEPA's ISC3 (USEPA(1995)), called ISC here and NRPB R91 (Clarke(1979) models), which are still in use and are of historical importance, has been investigated previously for HMIP by Carruthers et al(1996) using field LIDAR plume measurements as a basis.

The need for the present study has arisen with the formal release of the USEPA's AERMOD model (Cimorelli et al(1998a)) during 1998. Since the USEPA dispersion models are probably the most extensively used world-wide, the appearance of the first major modification to the

USEPA's basic dispersion model since the early 1980's is clearly a significant event. It is inevitable that the UK Environment Agency will receive applications for IPC authorisation with dispersion studies based on this model, particularly from multinationals for whom it is the main modelling tool. In the interests of both consistency in approach between authorisation applications and of appreciating the particular characteristics of this new model, it is highly desirable that systematic and dispersion studies be carried out, comparing its results with those using ADMS and the older models used in the UK.

The most important feature of the AERMOD model over its US predecessor, the ISC model, is its modification of the basic dispersion model to account more effectively for a variety of meteorological factors. In particular it uses the Monin-Obukhov length scale rather than the Pasquill-Gifford stability categories to account for the effects of atmospheric stratification. However, it remains essentially a Gaussian model. In many respects its basic dispersion model takes a similar approach to the ADMS model. Both models are derived from the same recent meteorological research base and handle plume dispersion in similar ways that depart from those of the older models. Beyond the basic dispersion model the two models diverge rather more. The AERMOD model largely fits the basic dispersion model into the old ISC model structure with similar (but in some cases slightly improved) procedures for dealing with other factors such as plume rise, building entrainment and terrain. The ADMS model has largely new procedures for dealing with all aspects of dispersion. In this sense, technically the greatest difference between the two models is probably in these secondary procedures to the main dispersion model. Both models also have (different) sophisticated pre-processors for handling the raw meteorological data and producing the required meteorological input parameters for the models.

The present study is therefore concerned most directly with the differences in dispersion calculations made with three dispersion models: the ISC, AERMOD and ADMS models. These are the short-range air dispersion models currently of greatest interest to the Agency. Though the NRPB R91 model is also historically important in UK practice, it has not been included here as it was felt that the ISC model (to which it is technically very similar) was sufficiently representative of its behaviour against the 'new generation' ADMS and AERMOD models.

This study also has the purpose of laying down a model testing protocol which can be used for future inter-comparisons. No study of this sort remains valid for much longer than the current versions of the relevant models. However, the need to understand the differences between models and versions of models will remain in the longer term. Historical changes are also important in regulatory practice, for example when authorisations made with an early version of a model come up for review and a new application uses either a different model or a different version of a model. Unless a standard inter-comparison protocol can be developed and adhered to, the longer-term relationship between models and versions of models will be lost.

2 MODELS AND MODEL VERSIONS USED IN THE INTERCOMPARISON

The models used in the intercomparison, the USEPA's ISCST3 and (recently introduced) AERMOD models and the UK ADMS model, will be discussed only briefly here since there are detailed descriptions available elsewhere. Technical details of specific facets of their operation are described in the relevant sections of the report. They are all essentially single or multiple point source models (though they all have alternative source options), which is the type of model of most interest in the Environment Agency's air pollution regulatory activities.

They have been tested in the single point source mode here. Though there is naturally an interest in multiple source dispersion in the Agency, this is normally estimated by simple addition of single point source calculations, so does not differ in principle from the single source calculations used here.

The ISC model (USEPA(1995), currently the ISCST3 version)) has been one of the USEPA's standard regulatory models since its introduction in the early 1980's and has been modified little since that period. It is by now probably the most widely used dispersion model of all time. Full details of the ISC model are published by the USEPA and these and the basic algorithms may be downloaded, free, from the USEPA web site (as for Cimorelli et al(1998a)). The input and output data handling in this form of the model is relatively basic and as a result there are also a number of 'commercial' versions which use the basic algorithms and provide much more sophisticated input and output facilities. One of these versions, the 'BREEZE Suite' due to the US Trinity Consultants Inc, was used in the present work and is the version in common use in the Environment Agency. A slightly modified version 3.2.2, issued in March 1999, was used in the present study. However, the basic structure of the ISC model, and its associated literature, has been altered very little since its inception. There are other 'commercial' versions of the ISC model currently available, for example that from Lakes Environmental (a Canadian based organisation). The ISC model uses only wind speed, direction and an atmospheric stability state (the Pasquill/Gifford category) supplied by the raw meteorological data, so does not need a meteorological pre-processor.

The USEPA AERMOD model was issued in a near-final form only towards the end of 1998. It is expected in due course to replace the ISC model as the USEPA's standard dispersion model. Full details of the model and of its meteorological pre-processor, AERMET, have been published (Cimorelli et al (1998b)). As with the ISC model, both the literature and the basic algorithms of both AERMOD and AERMET can be downloaded, free, from the USEPA web site (as for Cimorelli et al(1998a)), but the model has equally basic input and output data handling. Similarly therefore, 'commercial' versions of the model are available with much better input and output handling facilities. The first 'commercial' version of AERMOD, was issued by Trinity Consultants around the middle of 1998, in their 'BREEZE Suite'. A modified algorithm, working with a 32 bit software structure was issued in January 1999 and updated in June 1999 to version 3.2. It is this version which has been used in the present study. It incorporates the 'BREEZE' AERMET PRO meteorological pre-processor, version 3.02. Another 'commercial' version of AERMOD (strictly, as stated by the suppliers, a pre and post data processor incorporating the AERMOD algorithm) was also issued by Lakes Environmental ('ISC-AERMOD View', version 3.0 (Beta 0.7)) around the middle of 1999.

The ADMS model has been in substantial use in the UK for about six years and has passed through about eight versions since its first appearance. Though its development was largely funded by UK government agencies, it is treated as a proprietary model; there is no access to its algorithms or the details of its operation. Access to different stages of the calculation is also constrained. There are a number of papers describing its basic characteristics and a number of validation studies have been published by the suppliers, CERC. These can be found in the Bibliography attached to the Review of earlier intercomparison studies (Hall et al(1999c)). A substantial range of technical background documents has also been issued, though many of these have not been updated for some time. ADMS has sophisticated input and output data handling routines and its meteorological pre-processor is built-in. Version 3.0 (containing 'Interface Version 1.11'), the most recent, was issued around March 1999 by CERC, and has been used in the present study. ADMS contains its own meteorological pre-processor.

The basic details of the model versions and their dates of supply are summarised in Table 1, below.

Table 1. Basic details of model versions used in the study.

Model	Source	Version No	Date Issued
USEPA ISCST3	Trinity Consultants 'BREEZE Suite'	3.2.2	July 1999
USEPA AERMOD	Trinity Consultants 'BREEZE Suite'	3.2.2	June 1999
AERMET PRO (AERMOD Met pre-processor)	Trinity Consultants 'BREEZE Suite'	3.02	June 1999
ADMS	CERC	3.0	March 1999

3 MODEL INTERCOMPARISON PROTOCOL AND TEST METHODOLOGY

3.1 Background

In preparing a model testing protocol it is important to try and devise a programme containing a relatively limited number of dispersion calculations, but which is sufficient to expose any critical differences between models or versions of models. It is easy to carry out large numbers of calculations but to then be unable to interpret the results easily unless these can be reduced to some simpler understandable format. This is essentially the procedure adopted by Hanna et al(1991), Olesen(1995) and others in analysing model comparisons with experimental data, which are both numerous and scattered. However, in principle this should not be necessary when comparing models (rather than comparing models with experimental data) which can be done in relatively simple systematic ways.

Those aspects of dispersion model calculations that most affect regulatory practice were identified, in order to devise a simple test procedure of limited size.

The most important of these were considered to be:

Basic rates of plume dispersion in typical neutral, stable and unstable atmospheric conditions for low and high stacks.

Plume Rise

Large buoyant plume interaction with, and penetration of, the top of the boundary layer.

Building entrainment.

Effects of terrain on basic plume dispersion.

Surface roughness.

Ground level concentration contours for a single year's hourly meteorological data.

The last item is the way in which regulatory calculations are normally made, so this type of comparison is important. However, the individual aspects of the calculation cannot be readily deconvolved from annual calculations and must be tested separately.

There were also some other matters of interest, including coastal effects, multiple sources and groups of buildings. However, these were separate from the fundamental aspects of dispersion calculations above and are therefore not considered here. The UK Environment Agency also has a direct interest in predicting wet and dry deposition. However, this is a complex matter in its own right and was therefore left for separate consideration.

It is possible to devise a quite limited set of interlocking calculations, which should readily expose any major differences in behaviour between these fundamental aspects of a model. If the number of test cases is relatively small, they can be assessed by direct comparison without further recourse to complex analysis. The test conditions used for flat terrain were:

> Four boundary layer states, neutral strong wind (ca 10m s^{-1}) and neutral, stable and unstable light wind (ca 3m s^{-1}) for single condition calculations. The meteorological parameters, based on examples from site data, were fixed for these cases. The low wind speed case also used three boundary layer depths to test the interaction of a large buoyant plume with the top of the boundary layer.
>
> Discharges from elevated stacks at two heights, low (40m) and high (150m), each with a zero and a high buoyancy discharge (of approximately 2MW and 30MW respectively for the low and high stacks).
>
> Two building heights (attached to the lower stack) of 25m and 35m, of cubical and of wide form. The relative heights of stack and building were designed to produce significant plume partitioning and wake entrainment in one case (35m) and significant plume down wash but no direct wake entrainment in the other (25m).

The effects of terrain were examined using a single, neutrally buoyant discharge from a 40m stack, over terrain derived from a single real site. Both the overall and vertical terrain scale were varied in order to provide a range of surface slopes and relative heights of stack and terrain. It was felt that a real terrain presented a more realistic test of the models than a simple, idealised form. The terrain used was that of Porton Down in the UK, whose characteristics are well understood from a number of earlier studies. The test conditions used were a selection of six variations of the terrain and the discharge stack position; they are described in more detail in Section 3.8.

A total of about 260 single condition dispersion calculations were sufficient to cover the test cases for the three models and expose any essential differences between them. A further 63 calculations using a whole year's hourly data were sufficient to show any differences between models covering the essential parameters when the models are used in their normal manner for regulatory work.

It is not presumed that these test cases are sufficient to expose all nuances of the differences between models or versions of models. However, if dispersion calculations with this set of cases do not show any significant changes over the reference case, then it is unlikely that the model, or version of a model, will produce markedly different results in a regulatory calculation. If any particular case does show marked differences, then that facet of the model can be investigated in more detail if necessary.

The details of the test cases used are given in the rest of this section.

3.2 Meteorological data for annual hourly calculations

The annual dispersion calculations were carried out using a single year's hourly sequential meteorological data from Lyneham for 1995. This is an inland site and is the nearest Meteorological Office Site to Porton Down (about 40km to the NW), which was used for the dispersion studies with terrain. The station provided nearly complete hourly data, including cloud cover, so that it is suitable for dispersion modelling studies. The co-ordinates of the site are:

Latitude 51° 30'N, Longitude 1° 59'W

OS Grid Reference: 40061782

The aerodynamic roughness height, z_0, given for the site is 0.1m. The anemometer height is 10m. A wind rose for the site for 1995 is shown in Figure 1.

Standard Meteorological Office input data prepared for the ADMS and ISC models were used for the study. This data is then further processed as required by the models' own 'meteorological pre-processors'. ADMS type data are used as input to both the ADMS and AERMOD models.

3.3 Meteorological states for single condition test cases

For the single meteorological states, representative boundary layer conditions were selected from the hourly data for Lyneham, 1995 (as used for the annual dispersion calculations), to match the required conditions for the test cases.

Figure 2 shows a breakdown of the hourly data for Lyneham, 1995, by stratification, wind speed and boundary layer height, obtained from the ADMS meteorological data pre-processor. The distinction between convective, neutral and stable categories is defined by the ratio H/L_{mo} (where H is the boundary layer height and L_{mo} is the Monin-Obukhov length scale), taken here as,

Convective	$H/L_{mo} < -0.6$
Neutral	$-0.6 < H/L_{mo} < 2$
Stable	$H/L_{mo} > 2$

The choice of values of H/L_{mo} dividing the stratification states is somewhat arbitrary, but the values above are within the commonly accepted values. A dividing value of $H/L_{mo} = 1$ is used by the ADMS model to distinguish between stable and neutral boundary layers and of H/L_{mo} of –0.3 for neutral and unstable boundary layers; the dispersion calculation alters at these division points. AERMOD does not formally distinguish a neutrally stable case, having different basic equations for positive and negative values of L_{mo}. The choice of dividing boundary depends on how the boundary layer stratification characteristics are interpreted. In the stable case, Nieuwstadt (1984), using Zilitinkevich's formulation of the mixed-layer depth, derived,

$$H = c\sqrt{\frac{u_* L_{mo}}{f}}, \qquad ....(1)$$

where,
u_* is the friction velocity,
f is the Coriolis parameter (taken as $1.1 \times 10^{-4}\ s^{-1}$ at 53°N) and
$c \approx 0.35$ (that is, Nieuwstadt took the geometric mean of Monin-Obukhov and of Rossby scaling).

This can be rewritten to give,

$$\frac{H}{L_{mo}} = c\sqrt{\frac{kgq_0}{f\tau_0 c_p T}}, \qquad ....(2)$$

where,
k is Von Karman's constant (taken as 0.4),
g is gravitational acceleration,
τ_0 is the surface shear stress,
q_0 is the surface sensible heat flux,
c_p is the specific heat and
T is the surface temperature.

Used as a stability criterion, H/L, is thus equivalent to basing stratification on the ratio of the surface fluxes of sensible heat, q_0, and of surface shear stress, τ_0. For dry ground and with negligible advection, q_0 is determined by the surface radiation balance; τ_0 depends on the free-stream wind speed, the surface roughness and the current temperature profile. Taking H/L > 2 to define stable conditions, then with a surface sensible heat flux of -10 W m^{-2} the boundary layer will fall stable if $u_* < 0.17$ m s^{-1}. This seems a reasonable value. Such conditions are not usually in equilibrium and are more likely to be transitional states between the growth and decay of the boundary layer. Given such a heat flux, the surface would gradually cool until the temperature profile suppressed momentum transfer to the stable range; in the absence of such transfer, the wind shear would then increase until stratification broke down again. Such stable-neutral oscillations may occur repeatedly (Bennett et al (1999)).

Similar problems arise in unstable conditions. The boundary-layer depth here cannot simply be scaled from current surface conditions but is determined by its past history. The largest uncertainty in estimating q_0 is probably the availability of moisture at the surface: this determines the partition between latent and sensible heat flux. The predicted boundary layer depth then varies as the square root of the integrated sensible heat flux since dawn and of the initial potential temperature gradient. Both L and H thus depend upon variables which are not routinely determined and cannot therefore be estimated with any accuracy. In the unstable case such uncertainties can lead to errors in estimating rates of dispersion which can alter maximum ground-level concentration up to a factor of 2 or 3. The plume from most conventional sources is also unlikely to escape a well-developed convective boundary layer and its lower edge must usually reach the ground within about 10 stack heights.

It can be seen from Figure 2 that, at Lyneham, stable and convective boundary layers occurred mostly at low wind speeds, though there were a significant number of occurrences (a few hundred hours) of convective boundary layers at higher wind speeds, above 6.5m s^{-1}. Convective boundary layers showed a wide range of boundary layer heights up to 2000m, but nearly all the stable boundary layers were at or below 200m height. The neutrally stable boundary layers occurred over the full range of wind speeds and were mostly below 700m height, but some ranged up to 2000m. Convective, neutral and stable boundary layers occurred for approximately 26%, 45% and 25% of the time respectively, the residual 4% being classed as 'calms'.

Table 2 shows the boundary layer parameters used for the single condition test cases. The specific hours chosen and their basic meteorological states, on the left of the Table, were fed into the respective model meteorological pre-processors to find the Monin-Obukhov length scales, stability categories and boundary layer heights on the right of the Table. The 'neutral low wind speed' case chosen would be treated as mildly stable by the ADMS model, but is quite representative of the low wind speed conditions at Lyneham. These are rarely without some small degree of stability or instability. The stable boundary layer case chosen is not especially severe, but most representative of the Lyneham data where extreme stability conditions appeared relatively rare.

It will be noted that in each case the ADMS and AERMOD meteorological pre-processors predicted significantly different values of both the Monin-Obukhov length scale and all the models differed in their estimated boundary layer heights. The ADMS model predicted low boundary layer heights for the stable and the low wind speed neutrally stable cases of 90m and 130m height respectively, though the AERMOD model predicted higher boundary layers of 188m and 375m respectively for the same conditions. It must be of some concern that, although ADMS and AERMOD broadly agreed in their predictions of H/L in stable or slightly stable conditions, they disagreed by a factor of 2 or 3 in either term separately. The analysis above suggests that there is probably a commonality in each model in its relative estimates of Q_0 and τ_0. A fourfold uncertainty in these would then convert into a twofold uncertainty in L and H; but no error in H/L. For dispersion near the surface, these model differences are of limited concern. However, for elevated sources they can be more critical, for example in determining whether or not a buoyant plume escaped the boundary layer (this is discussed in Appendix 2).

Table 2. Boundary layer parameters used for the single condition test cases . (Assumed z_0 for site 0.1m)

Boundary Layer Type	Date	Hour	Temp (°C)	RH (%)	Wind Speed* M s^{-1})	Cloud Cover (oktas)	UK ADMS[1]			AERMOD[2]				ISC[3]		
							$1/L_{mo}$ (m^{-1})	H (m)	H/L_{mo}	$1/L_{mo}$ (m^{-1})	Zic[4] (m)	Zim[5] (m)	H/L_{mo}	H[6] (m)	P[7]	P-G[8]
Neutral - Low Wind Speed	27-Sept	06	10.9	99	3.6	7	0.01	130**	1.3	0.004	-	375	1.5	526	4	D
Neutral - High Wind Speed	19-Jan	16	7.6	70	9.8	7	0.001	1228	1.23	0.0003	-	1685	0.51	1603	4	D
Stable	30-Oct	22	6.9	88	3.1	1	0.03	90**	2.7	0.01	-	188**	1.9	517	5	E
Unstable	29-July	12	23.5	54	3.1	4	-0.03	700	-21	-0.01	1126	712	-11.2	3697	2	B

1. Output from ADMS meteorological pre-processor.
2. Output from AERMET PRO meteorological pre-processor.
3. Output from UK Meteorological Office data in ISC format.
4. Zic - Height of convectively generated boundary layer. } (The AERMOD model takes the larger of the two values)
5. Zim - Height of mechanically generated boundary layer. }
6. Boundary layer height given for both ‘rural’ and ‘urban’ values.
7. Smith’s stability parameter P (Clarke (1979)) as output from Meteorological Office ISC data.
8. Pasquill-Gifford Stability parameter. Derived from P in Clarke (1979) Figure 2.

* At a reference height of 10m.

** Boundary layer height increased to 200m for some dispersion calculations (see text).

Using the ADMS model in these cases, the plume from the 150m stack would then penetrate the boundary layer, in principle producing zero plume concentrations at the ground. Rather than merely leave this as an extreme example of the differences between model calculations, it was felt preferable to have all discharges within the boundary layer for comparative purposes. All the models' lowest boundary layer heights were therefore set at 200m, the stable and neutral boundary layers in ADMS and the stable boundary layer in AERMOD. In the latter case the change (from 188m) was felt to be of little significance. However, in order to check any effects this might have on the ADMS model calculations, two boundary layer heights, of 90m and 200m were used in the stable cases for some of the basic dispersion calculations. Though there were some limited changes in the calculated concentrations at the ground between the two boundary layer height assumptions, these were not large enough to affect the conclusions of the study. Considering the differences in calculated boundary layer height between the models, this alteration was felt to be within the tolerance of the estimates. The results for different boundary layer heights are discussed in detail in Section 4.2.

3.4 Model input parameters and stack discharge conditions

The models required values of a number of input parameters in addition to the basic meteorological data, as well as the stack discharge conditions. The additional input parameters used in the study are shown in Table 3; these were constant for all models and test conditions. The molecular weight and specific heat used were those of ambient air. Because of the models' input requirements for an identifiable emission, this was input as 'sulphur dioxide' at a unit emission rate of 1000g s^{-1}. However, this does not affect the results of the study. The calculated concentrations are given in normalised form for the single condition calculations (see Section 4.1) and the annual calculations give concentrations in mg m^{-3} for this unit discharge. The surface roughness, z_0, of 0.1m used is that quoted for Lyneham. It is also the value for the 'Rural' surface roughness in the ISC model.

The stack discharge conditions used are shown in Table 4. The discharges with buoyancy are consistent with those of typical combustion plant; the lower buoyancy with that of a small generation unit (of below 30MW thermal input) or waste incinerator and the higher buoyant discharge with that of a large waste incinerator or medium-sized (of 300-400MW thermal input) generating plant. The discharges without buoyancy were set at low emission velocities to minimise plume rise. In principle the smaller the source diameter and the lower the efflux velocity, the lower is the plume rise. However, both the ADMS and AERMOD models incorporate a 'stack tip downwash' correction due to Briggs (1973) which lowers the effective source height below that of the stack when efflux velocities are low compared with the wind speed. The discharge velocity was set sufficiently high (at 5 m s^{-1}) to minimise this. There was a resultant small plume rise of the neutrally-buoyant plume due to its discharge momentum. Approximate values of the plume rise at a distance of 500m, calculated using the Briggs plume rise formulae (Briggs(1975)) in neutral stability, are shown at the bottom of Table 4 for the two wind speeds used in the neutrally stable boundary layer test cases. These should be close estimates of the plume rise in the study. Two of the models, ISC and AERMOD, use the Briggs plume rise formulae. The ADMS model uses a more complex recursive procedure; however, from available information described in the review preceding this study (Hall et al(1999c)) its plume rise estimates appeared little different from those of the Briggs formulae.

Table 3. Additional model input parameters.
Constant inputs for all models and test conditions.

Parameter	Value
Surface roughness (z_0)	0.1m
Latitude (Lyneham)	51.5°N
Longitude (Lyneham)	1.983°W
'Pollutant'	SO_2
Specific Heat, C_p	1012J °C^{-1} kg^{-1}
Molecular weight	28.96
Deposition velocity	0
Washout coefficient	0
Emission rate	1000g s^{-1}

Table 4. Stack discharge conditions used in the study.

Parameter		40m stack		150m stack	
		No buoyancy	With buoyancy	No buoyancy	With buoyancy
Stack height	(m)	40	40	150	150
Stack diameter	(m)	1	1	1	4
Exit temp	(°C)	15	130	15	130
Exit velocity	(m s^{-1})	5	25	5	25
Heat Release	(MW)	0	2	0	32.3
Discharge Momentum *	(m^4 s^{-2})	19.3	345	19.3	5515
Plume rise (m) At 500m distance**	3.5 m s^{-1} ***	15	79	15	199
	9.8 m s^{-1} ***	7.3	30	7.3	75

* As defined in HMIP Guidance Note D1 (HMIP(1993)).
** Calculated using the Briggs plume rise formulae for neutrally stable atmospheres.
*** Wind speed at 10m height.

It can be seen from Table 4 that the buoyant discharges produced a substantial plume rise, even at the higher wind speed. The high plume rise of the taller stack's buoyant discharge was sufficient for the plume to reach the top of the boundary layer, so that this interaction could be investigated. The neutrally buoyant discharges also produced some plume rise due to the discharge momentum. For the higher stack, the effective increase in stack height was small, 10% or less, but for the 40m stack it was a larger proportion, at about 38% and 18% of the stack height respectively at the low and high wind speeds. Thus the effective height of the plume from the lower (40m) stack for the neutrally buoyant discharges was typically between 45m and 60m.

3.5 Test cases for plume rise and boundary layer interaction

The effects of plume rise were investigated using the buoyant discharges from the stacks as outlined in Table 4. Buoyant discharges from the 150m stack were also used to investigate the plume interaction with the top of the boundary layer. In these cases the test conditions from Table 2 were used, except that the boundary layer height was additionally varied from 200m, to 700m and then to 1200m, leaving the other boundary layer parameters unaltered.

This allowed a range of interactions of this rising plume with the top of the boundary layer between penetration and complete capture within the boundary layer.

3.6 Test cases for building entrainment

Because most elevated stack discharges are associated with buildings, the entrainment of plumes in building wakes is of great practical importance and is often the dominant factor controlling acceptable stack heights, especially of low level stacks, represented here by the 40m discharge stack. The most significant feature of building entrainment in most regulatory studies is the plume entrainment in the building wake or its rapid downwash from elevated sources, since this generates high near-field concentrations at the ground.

In order to test this behaviour, the intercomparison programme used the 40m height stack with a neutrally buoyant discharge, adjacent to buildings of 25m and 35m height. By also taking the 40m stack basic dispersion case without a building and an additional case with the building but zero stack height, the set of test cases covered:

> complete plume entrainment (zero stack height),
> varying partial plume entrainment and downwash (using 25m and 35m building heights), and
> zero plume entrainment or downwnash (no building).

The stack and building heights were low compared with the boundary layer height, which is typical of these cases in practice. It is then mainly the relative heights of building and stack that are of interest; the absolute heights should not greatly affect the plume/building interaction. For this reason only the single, lower stack height has been used.

Two building shapes were used for the building entrainment cases, a cube and a low, wide structure of width seven times its height. The cubical shape, though relatively uncommon in practice, has been subject to thorough study of its aerodynamic and dispersion (entrainment) characteristics, mostly in wind tunnel experiments but also in field trials. However the low, wide form is the most commonly occurring; the particular form used here has also been the subject of both field and wind tunnel dispersion investigations (Higson et al(1994, 1996), Hall et al(1996)).

Calculations were made only with the building set square across the wind, though the models do account for variable effects of wind direction, as shown for example by Harvey and Obasaju(1999). However, all the models treat near field building entrainment in quite primitive ways, even the most sophisticated (the ADMS model) still approximates the building form (even of groups of buildings) into an approximately equivalent rectangular block. Under these circumstances it was felt that limited purpose would be served by looking in any detail at these effects. A full set of intercomparisons were made with the cubical building shape but only one case with the low wide building (using a 35m building height).

3.7 Test cases for surface roughness

These test cases comprised a single additional calculation for the three models using a surface roughness (z_0) of 0.5m in addition to the value of 0.1m used in all the other calculations. For the ISC model there is only a choice of 'rural' or 'urban' surface roughnesses, which correspond approximately to these values. Calculations were carried out for a single case for the 40m stack with a neutrally buoyant discharge and for the 150m stack with a buoyant discharge, using one year's hourly sequential meteorological data.

3.8 Test cases for terrain

The commonly expressed rule of thumb (albeit rather approximate) is that terrain with slopes below about 0.1 has only limited effects on dispersion. On this basis most of the UK is topographically flat and so terrain is of limited interest in most UK dispersion studies. However, in the significant minority of areas where terrain is more severe its effects on dispersion can be very marked and it is often the critical feature governing dispersion behaviour and the determination of adequate discharge stack heights. Because of its multivariate nature it is difficult to devise a limited set of simple intercomparison cases that will adequately test a terrain dispersion model. The approach used here has been to devise a limited set of variants on a real basic terrain. The choice of a real terrain has been deliberate as this possesses an asymmetry and local variability that presents a more realistic test of a dispersion model than a symmetrical, well-ordered theoretical form.

The terrain chosen for the present study was that of Porton Down, whose meteorological and dispersion characteristics have been well studied over many years. This was the site on which Pasquill and his colleagues carried out many early dispersion experiments and has been the subject of continued attention since in a variety of research projects, such as the MADONA trials (Cionco et al(1995)) which investigated low wind speed behaviour over terrain. The steepest gradients are about 0.14.

The test procedure used here was to take the basic terrain of the central region of Porton Down and to modify it simply to generate six test cases. In each case the model domain consisted of a terrain feature located on a flat plain. The elements of the terrain around the outer regions of the calculation area were reduced to a uniform height at the edges of the terrain domain. This format was less site-specific and clearly distinguished between the plume being over the terrain or flat ground. The stack could be sited on flat terrain and the relative distance to terrain base and terrain peak more clearly defined. It also avoided any possible effects on the calculations due to a change in terrain height at the boundary of the calculation domain. This was considered important mainly for ADMS. Full details of its calculation methodology were not available, but the wind field calculation is based on a Fourier transform of the surface. This type of calculation can be sensitive to variations in height at the domain boundary.

The plume source was the 40m stack with a neutrally buoyant discharge. The basic terrain had a height range of 40m, the same as the stack, so that, allowing for the limited plume rise, the plume should be in contact with the upper levels of the terrain in the absence of any modifications to the streamline or dispersion patterns. In terms of generating dispersion test cases, the absolute height of the stack and the terrain is not of great importance if it is relatively small compared with the boundary layer height. This is mostly the case in the UK, where the highest terrain (Ben Nevis) is about 1300m ASL. The main parameters governing dispersion are the ratio of stack height to terrain height and (in stratified flows) the ratio of terrain height to Monin-Obukhov length scale, h/L_{mo}.

The six test terrains are shown in Figure 3 (in perspective) and Figure 4 (in plan and elevation). The stack positions are marked on Figure 4. They constitute,

Three levels of gradient slope: 'normal' (as in the original Porton terrain), half and twice normal,

Three levels of terrain height: equal to, greater and less than the stack height,

Three distances from the stack to the steepest part of the terrain.

They are described briefly below: the discharge stack height was 40m in all cases and was placed upwind of the terrain;

> Case 1. Terrain and stack heights equal (at 40m), terrain slope 'normal' (that is, as on the Porton site). The stack was positioned upwind close to the terrain, at its rising edge, 600m from the centre of the terrain. In neutral stability the plume's first contact with the ground would have been at around this distance in the absence of the terrain, so that the plume contacted the rising terrain.
>
> Case 2. Terrain and stack heights as in Case 1 (40m), except that the stack was positioned further upwind, 800m from the centre of the terrain. In neutral stability the plume's maximum concentration would have been at around this distance in the absence of terrain.
>
> Case 3. Terrain and stack height as in Case 1 (40m), except that the stack was far upwind of the terrain, 1200m from its centre. At this distance the plume was in contact with the ground before reaching the terrain.
>
> Case 4. Terrain height halved over Case 2, leaving the planform the same, so that the terrain slopes were halved and the height reduced to 20m. The stack height was then twice the terrain height. The stack height and position were as in Case 2, 40m height 800m upwind of the centre of the terrain. The terrain slopes were at the margin of those commonly thought to be significant to dispersion.
>
> Case 5. Terrain height doubled over Case 2, to 80m, leaving the planform the same so that the slopes were doubled; the maximum slopes were then around 0.28 and the stack height was half the terrain height. The stack position was as in case 2, 800m upwind of the centre of the terrain.
>
> Case 6. Terrain height and planform doubled over that of Case 2, so that the terrain slopes remained the same. The stack height was then half the terrain height. The stack was 800m upwind of the maximum of the terrain height, so it was then positioned on the terrain. The stack height was 40m above the local terrain height, which was about 17m above the ground plane.
>
> Gaussian Hill. A terrain of gaussian cross section with the same mean height and cross sectional area as the terrain of Case 2. This was essentially a smoothed form of Case 2, so that the effects of the irregularities in the terrain could be distinguished.

The choice of grid spacing, both for the terrain and the dispersion calculation, can affect dispersion calculations over terrain. For AERMOD and ISC there is no particular limitation on the size of the receptor grid used in a model run with terrain, except that imposed by the available computer power. A number of such grids can be used at the same time but, to maintain a consistent approach between the models in the study and to avoid additional complexity, only a single grid has been used. Only one grid is required: this is the receptor grid. Terrain (and in the case of AERMOD, the receptor height scale) information is interpolated onto this grid before the model run. The procedure is carried out within the model user interface and data are interpolated from OS files to the required grid. This was not possible for the modified terrain generated for the study. Interpolation of terrain data and calculation of receptor height scales (from data at 40m spacing) was therefore carried out separately and the resulting arrays imported into AERMOD and ISC via the user interface.

ADMS requires two grids. The terrain grid (which can be created directly from OS data) is used in the Fourier transform calculations in FLOWSTAR. For this reason it is restricted to a

$2^n x 2^n$ form, for example 64x64. The second grid contains the dispersion model receptor points and the size limitation on this grid is the same as for a standard flat terrain run, 32x32, with the additional restriction that it must be at least 100m smaller than the terrain grid in both horizontal directions.

In order that the same calculation receptor grids were used in all three models, the restrictions of the ADMS model were used to determine the receptor and hence terrain grid sizes in the other two models. For the single condition calculations the input terrain information for ADMS was at 40m intervals for cases 1 to 5 and 80m intervals for case 6. The concentration receptor grids were at 100m spacing for cases 1 to 5 and 200m spacing for case 6. For the annual calculations, a new receptor grid, centred on the source, was used to include the results from all wind directions. A 100m spacing grid was used for all these cases. The terrain grid dimensions in ADMS had to be changed as it is necessary to rotate the output grid inside the terrain grid while still maintaining the 100m buffer distance between the terrain and receptor grids. A terrain grid of 160m spacing over a 32x32 grid was used for all cases as calculation times otherwise became excessive. The AERMOD and ISC receptor grids were identical to the ADMS receptor grids (100m and 200m) but terrain data was interpolated onto them from the original 40m terrain grid.

The information obtained by the model user on the effect of the terrain on the predicted concentrations is governed by the receptor grid density: equally, as the terrain grid spacing increases, less information is available to the dispersion models. Hence it is important to select grid sizes which resolve the features of the domain of interest to an adequate level. Little guidance is offered by the model suppliers on this issue. The final terrain and receptor grids used in the study were considered to be sufficient for the terrain used, within the practical limitations imposed by the models. However, the authors are aware of the importance of the sensitivity of the model results to grid resolution (terrain and receptor), although this was outside the direct remit of this study.

4 RESULTS OF INTERCOMPARISON

4.1 Data presentation

Tables 5 and 6 lay out details of all the intercomparison calculations made. For the calculations in single meteorological conditions, plots are normally provided of the normalised plume centreline ground level concentration with distance from the source and contour maps of the related ground level concentrations. Calculations of annual statistics are given as concentration contour plots. Normally, values of the annual mean, 98%ile, 99.9%ile and 100%ile are given. Results of all the calculations are also given as bar charts and tables of maximum concentrations with their distances from the source.

Following Slade (1968) and Bruce-Turner (1994), all the concentration measurements for the single state cases are normalised with respect to the pollutant emission rate and reference wind speed and are given in the form,

$$K = \frac{\chi u}{Q}, \qquad ....(3)$$

where χ is concentration,
u is wind speed and
Q is the pollutant emission rate.
K has units of m^{-2}.

The annual calculations of concentration cannot be normalised in this way as the wind speed is variable from hour to hour. These cases therefore give concentrations in mg m^{-3} for the standard emission rate of 1000g s^{-1} noted in Table 3.

The main body of the report gives graphical results only for a subset of the full calculation set, sufficient to show the critical features of the intercomparison. However, all values of the various maxima and their distances from the source are given in the bar charts and tables.

4.2 Basic rates of dispersion and plume rise

Figures 5-11 and Table 7 show the results of this part of the intercomparison for the single state conditions. Plots of plume centreline ground level concentrations from the two stack heights, with and without plume buoyancy in flat terrain, are shown in Figures 5-8. A bar is shown indicating the order of 'factor of 2' differences in concentration. This is the order of difference commonly quoted as the tolerable limit of accuracy of model/model or model/observation intercomparisons. It is based mainly on practical experience and has limited theoretical justification. It is also a significant difference from a regulatory viewpoint. In fact it does relate to the discontinuous nature of the ISC and other models using the Pasquill/Gifford categories. The steps in plume spread rates from one stability category to another in these models correspond approximately to factors of three in plume concentration. The determination of these categories is not precise, depending, for example, on the way in which surface heat transfer and cloud cover are estimated or the height at which the reference wind speed is taken (some examples of this are noted in the review accompanying this report).

Thus any single condition intercomparison using these models could show differences of this order as a matter of course. However, the ADMS and AERMOD models grade stability as a continuum, so there is no direct justification for such discontinuities to exist in any comparison between them, as distinct from comparisons with the ISC's Pasquill/Gifford category model.

Most of the concentration/distance plots in Figures 5-8 showed ordered continuous curves with a single peak, as would be expected. The ADMS model for the 150m stack and the unstable boundary layer showed a step discontinuity in concentration at a distance of about 20km from the stack for both buoyant and neutrally buoyant discharges (the bottom left plots in Figures 7 and 8). This was due to a doubling of the calculation grid size in order to extend the initial calculation beyond this distance.

The smallest differences between the three models occurred in the unstable and in the neutrally stable strong wind speed cases, where the maximum concentrations fell within the 'factor of two' difference. The stable case showed a marked downwind shift in the position of the maximum concentration and the models showed much greater differences between both their maximum concentrations and its distance from the stack. The neutrally stable atmosphere, low wind speed cases showed greater differences between the models than their corresponding high wind speed cases, possibly because of differences in assessing the stability in the low wind speed case; though both ADMS and AERMOD would have treated this case as mildly stable. The addition of plume rise to the two discharges markedly reduced concentrations at the ground (by about an order of magnitude) but did not otherwise greatly affect the differences between the models. Since two of the models (ISC and AERMOD) use the same plume rise formulae (due to Briggs(1975)) and the ADMS model seemed to produce plume rise estimates that were little different (Hall et al(1999c)), this is perhaps as it should be. There was no clear pattern of one model producing consistently higher or lower

Table 5. Details of intercomparison calculations. Single hour calculations.

Details	Neutral, Low wind speed	Neutral, High wind speed	Unstable	Stable
Flat terrain, no building				
40m stack, no buoyancy	X	X	X	X
40m stack, with buoyancy	X	X	X	X
150m stack, no buoyancy	X	X	X	X
150m stack, with buoyancy	X	X	X	X
Flat Terrain, with building				
Zero source height, no buoyancy, 35mx35mx35m building	X	X		
40m stack, no buoyancy, 25m x 25m x 25m building	X	X		
40m stack, no buoyancy, 35m x 35m x 35m building	X	X		
40m stack, no buoyancy, 35m x 35m x 245m building	X	X		
Boundary Layer Interaction				
150m stack, with buoyancy, 200m bl height	X			X
150m stack, with buoyancy, 700m bl height	X		X	
150m stack, with buoyancy, 1200m bl height	X		X	
With terrain (all 40m stack, no buoyancy)				
Gaussian hill	X		X	X
Case1	X		X	X
Case2	X		X	X
Case3	X		X	X
Case4	X		X	X
Case5	X		X	X
Case6	X		X	X

Table 6. Details of intercomparison calculations. Annual calculations.

Details	$z_0 = 0.1m$	$z_0 = 0.5m$
Flat terrain, no building		
40m stack, no buoyancy	X	X
40m stack, with buoyancy	X	
150m stack, no buoyancy	X	
150m stack, with buoyancy	X	X
Flat Terrain, with building		
40m stack, no buoyancy, 25m x 25m x 25m building	X	
40m stack, no buoyancy, 35m x 35m x 35m building	X	
With terrain (all 40m stack, no buoyancy)		
Gaussian hill	X	
Case1	X	
Case2	X	
Case3	X	
Case4	X	
Case5	X	
Case6	X	

concentrations than the others. Of the 16 test cases in Figures 5-8, ISC produced the highest maximum concentrations on 9 occasions, ADMS on 5 and AERMOD on 2. Of the distances to the maximum concentrations, ISC produced the highest values on 7 occasions, ADMS on 1 and AERMOD on 8. Thus on a majority basis, the ISC model tended to produce the highest concentrations and ISC and AERMOD the greatest distances to the maximum, but the two conditions were not usually concurrent. The plots generally showed the AERMOD and ADMS modelled concentrations to be closer to one another than to the ISC model.

Figures 5-8 also show the effects on the ADMS model calculation of fixing the boundary layer height at 200m for the stable case as calculations for both this and the originally estimated boundary layer heights are given. For the 40m stack discharges there were clear differences between the calculated centreline concentrations. These differences were relatively small for the non-buoyant discharge in Figure 5, but for the buoyant plume in Figure 6 maximum concentrations were about 30% higher. However, the positions of the concentration maxima were similar and the relative behaviour of the three models remained the same. With the 150m stacks, differences between the plume centreline concentrations at the ground were relatively small, both with and without plume buoyancy. This occurred despite the stack being respectively below and above the boundary layer in the two cases. For the non-buoyant plume in Figure 7, the small difference in ground level concentration between the two boundary layers implies some re-entrainment from above the lower boundary layer.

The buoyant plume in Figure 8 showed 95% penetration of the 200m boundary layer, so that in this case nearly the same small residual component of the plume must have been re-entrained through the lower boundary layer and dispersed back to the ground, producing the quite low concentrations that occurred there. For the present purposes the main conclusion is that though the use of the different boundary layer heights for the stable boundary layer altered the ground level concentrations, it did not affect the overall differences between the models.

The concentration contour maps in Figures 9 and 10 match the cases without buoyancy in Figures 5 and 7 and show the surface area covered by the plumes. The contour values are identical in the individual plots and the stack position is marked with a star. There was a difficulty in interpreting the data due to contouring problems experienced using the software package (SURFER 6, used in all the models for contour data presentation) due to the limited number of grid points within the plume area (usually 30 x 30). A clear example of this is in the unstable case of Figure 10, where all three models showed steps in contours close to the stack. The equivalent case in Figure 9, for the lower stack, showed the same effect but less severely. The apparently blunt appearance of the upwind edge of the plume contours in some cases was also largely due to contour fitting problems. Allowing for this, there remained significant differences between the models' plume area coverage. Overall (but not consistently) AERMOD produced the widest plumes and ISC the narrowest, with marked differences in both the areas of highest concentration and in the positions of the contours.

The numerical differences between the different model maximum concentrations and their distances from the source are given in Table 7, which also shows ratios of these values between the models, using AERMOD as the reference. These ratios are also shown in the bar charts of Figure 11. The order of presentation of the data in each plot in Figure 11 is that of increasing effective plume height, due to the combination of stack height and plume rise, so that any trends from this cause can also be seen. The broken lines on the plot are for a factor of two variation in the ratio.

Table 7. Maximum concentrations and their distances from the source for basic dispersion and plume rise cases. (Concentrations normalised as (m^{-2}) x 10^6, (Equation 3))

Scenario	Model/Ratio	Neutral, Low wind speed		Neutral, High wind speed		Unstable		Stable	
		Distance to Maximum (m)	Maximum Concentration (m^{-2} x 10^6)	Distance to Maximum (m)	Maximum Concentration (m^{-2} x 10^6)	Distance to Maximum (m)	Maximum Concentration (m^{-2} x 10^6)	Distance to Maximum (m)	Maximum Concentration (m^{-2} x 10^6)
40m stack, No buoyancy	**AERMOD**	1000	24.5	500	52.4	300	38.9	3000	12.1
	ADMS	700	24.8	500	44.3	200	74.1	1400 (1700)*	9.5 (7.9)*
	ISC	900	49.8	800	60.0	300	62.3	1900	19.6
	ADMS/AERMOD	0.70	1.01	1.00	0.85	0.67	1.90	0.47 (0.57)*	0.79 (0.66)*
	ISC/AERMOD	0.90	2.04	1.60	1.15	1.00	1.60	0.63	1.62
40m stack, With buoyancy	**AERMOD**	2900	4.7	650	31.4	350	11.8	10000	2.2
	ADMS	2100	4.4	550	28.4	300	22.0	3400 (4900)*	2.2 (1.5)*
	ISC	2100	10.9	1200	27.2	600	16.7	3900	5.4
	ADMS/AERMOD	0.72	0.94	0.85	0.90	0.86	1.86	0.34 (0.49)*	1.02 (0.69)*
	ISC/AERMOD	0.72	2.32	1.85	0.87	1.71	1.42	0.39	2.49
150m stack, No buoyancy	**AERMOD**	12900	0.5	3400	2.0	600	5.3	66000	0.2
	ADMS	10000	0.3	1900	3.2	700	6.9	29000 (32000)*	0.1 (0.1)*
	ISC	5900	1.9	5400	2.0	900	5.6	14000	0.6
	ADMS/AERMOD	0.77	0.56	0.56	1.58	1.17	1.30	0.44 (0.48)*	0.47 (0.35)*
	ISC/AERMOD	0.46	3.71	1.59	1.02	1.50	1.05	0.21	3.29
150m stack, With buoyancy	**AERMOD**	55400	0.07	5400	0.8	900	0.9	180000	0.03
	ADMS	44000	0.03	3000	1.2	4000	0.7	80000 (80000)*	0.01 (0.01)*
	ISC	25400	0.23	10900	0.7	2900	0.9	39000	0.14
	ADMS/AERMOD	0.79	0.43	0.56	1.56	4.44	0.68	0.44 (0.44)*	0.33 (0.33)*
	ISC/AERMOD	0.46	3.29	2.02	0.89	3.22	0.96	0.22	4.67
AVERAGE VALUES (4 scenarios)	**ADMS/AERMOD**	**0.75**	**0.74**	**0.74**	**1.22**	**1.79**	**1.44**	**0.42 (0.50)***	**0.65 (0.51)***
	ISC/AERMOD	**0.64**	**2.84**	**1.77**	**0.98**	**1.86**	**1.26**	**0.36**	**3.02**

* ADMS stable results for two boundary layer heights, first value for H = 200m, second value (in brackets) for H = 90m

Comparisons of maximum concentrations fall into two groups. In the stable and low wind speed neutrally stable cases, AERMOD produced (except marginally in one case) persistently higher concentrations than ADMS and persistently much lower concentrations than ISC. In the unstable and high wind speed neutrally stable cases differences between the models were smaller and less consistent, but generally AERMOD produced lower concentrations than ADMS and relatively similar or lower concentrations than ISC. Though the statistic has limited meaning in the intercomparison, the overall average of ratios for AERMOD/ADMS was close to unity. That for AERMOD/ISC was about one half. There were distinct trends in the ratios of concentrations with plume height apparent in Figure 11. In all but the high wind speed neutrally stable case AERMOD produced proportionately higher concentrations than ADMS with increasing plume height. The variation of AERMOD to ISC concentrations with plume height was more variable, the only pronounced trend was in the stable case, when AERMOD produced proportionately lower concentrations than ISC with increasing plume height.

The ratios of distance to maximum concentration in Figure 11 and Table 7 showed variations in this distance mostly within a factor of two. The overall averages of the ratios for ADMS/AERMOD were about 0.9, so that overall AERMOD produced relatively greater distances to the maximum, and for ISC /AERMOD about 1.2, so that overall AERMOD produced shorter distances to the maximum. However, these means covered large variations. There were three cases where AERMOD produced significantly greater distances than ADMS and one case where it was significantly less. Against ISC, AERMOD showed two cases of significantly greater distances and two with significantly shorter distances. Only the unstable case showed a marked variation of the distance with plume height, where AERMOD produced relatively shorter distances to the maximum with increasing plume height than either ADMS or ISC

4.3 Buoyant plume/boundary layer interaction

Figures 12 and 13 show ground level plume centreline concentrations of the buoyant discharge from the 150m source height at low wind speeds in boundary layers of depths 200m, 700m and 1200m. Figure 12 shows results for neutrally stable boundary layers and Figure 13 shows results for stable and unstable boundary layers. There are no data for an unstable boundary layer of 200m depth as this state did not occur in the Lyneham data: it is impracticable except as a short term transitional occurrence. Similarly, there are no data for stable boundary layers of 700m and 1200m depth as these states did not occur either in the Lyneham data. The AERMOD and ADMS models also allowed optional calculations for ‘specified’ and ‘implicit’ capping inversions to the boundary layer. In the first case the operator sets a capping inversion for the boundary layer, which the plume will not penetrate; essentially a conservative modelling assumption. In the second case, the model makes its own decision over the degree of plume penetration. The related ground level concentration contours are given in Figures 14, 15 and 16 for the 200m, 700m and 1200m boundary layer depths respectively.

For the neutrally stable boundary layers in Figure 12, at the lowest boundary layer depth of 200m, results are shown only for AERMOD and ADMS. The ISC model predicted complete penetration of the boundary layer so no plume concentration was registered at the ground. Both AERMOD and ADMS predicted initial contact of the plume with the ground at 3.5-4.5km distance, after which concentrations at the ground rose continuously over the 30km range of the calculation. Up to 20km distance there was more than an order of magnitude difference between ground level concentrations from the two models. Beyond this the concentrations were converging. There was little difference between the results for the other two boundary layer depths, though the three models gave markedly different individual predictions. Calculated concentrations at the two boundary layer depths were in fact identical for ISC, which is not sensitive to boundary layer depth, very nearly so for AERMOD and a little different for ADMS, which showed slightly higher concentrations for the deeper boundary layer. It is apparent from this that varying boundary layer depths above 700m had little effect on the concentrations at the ground, so that interaction between the plume and the top of the boundary layer was no longer significant within the 30km range of the calculations. Major differences in concentration at the ground between AERMOD and ADMS remained, mainly because of marked differences between the distances at which the respective plumes first contacted the ground. Concentrations at the ground from the ISC model were closest to those for ADMS, but large differences remained between these two models.

In the stable boundary layer case in Figure 13, the ISC model predicted plume reflection from the top of the boundary layer, thus producing concentrations at the ground. Differences in concentrations between using the specified and implicit capping inversion options in AERMOD and ADMS indicated the proportion of the plume reflected or penetrated at the inversion. It can be seen from this that the proportion of the plume reflected by ADMS was apparently much more than for AERMOD as concentration differences between the two capping inversion choices were significantly smaller for ADMS. However, the relative concentrations at the ground were also influenced by the relative rates at which the AERMOD and ADMS plume fractions retained in the boundary layer dispersed back to the ground and these were also probably different. It was only beyond 40-50km distance that concentrations from the three models showed some convergence as the plumes started to fill the whole boundary layer: at shorter distances, differences between ground level concentrations exceeded orders of magnitude.

The distinctive features of the dispersion patterns in the 200m deep boundary layers of Figures 12 and 13 were, firstly, the rise of the plume to the top of the boundary layer before its contact with the ground. Secondly, the complete or partial penetration of the plume through the boundary layer's capping inversion. Finally there was the subsequent dispersion of the plume (or its residual part) back down to the ground. At the greater distances of the calculation, the plume was becoming uniformly distributed through the boundary layer and ground level concentrations then depended only on lateral rates of plume dispersion and the proportion of the plume retained in the boundary layer. This is discussed in more detail in Appendix 2.

Dispersion in the unstable boundary layers of 700m and 1200m depth is shown in Figure 13. Results for the two capping inversion choices were essentially identical, so that this factor played no part in the dispersion calculation for boundary layer depths beyond 700m and it can be presumed that there was no significant plume penetration through the boundary layer predicted. Concentration patterns for the ADMS and AERMOD models were similar at the two boundary layer depths, but not identical (ISC, as noted above, is not sensitive to the boundary layer depth). The maximum concentrations were similar but the ADMS model plume contacted the ground sooner in the deeper boundary layer. Concentrations from both AERMOD and ADMS at longer ranges were reduced by about a factor of two in the deeper boundary layer. This is consistent with uniform plume dispersion within the almost doubled depth of boundary layer.

The related ground level concentration contours are shown in Figures 14, 15 and 16. In the stable and neutrally buoyant 200m deep boundary layers of Figure 14, the ADMS plumes

Table 8. Maximum concentrations and their distances from the source for plume/boundary layer interaction cases. (Concentrations normalised as (m^{-2}) x 10^6, (Equation 3))

Boundary Layer Height (m)	Maximum Values	Neutral			Unstable			Stable		
		AERMOD	ADMS	ISC	AERMOD	ADMS	ISC	AERMOD	ADMS	ISC
200	Conc (m^{-2} x 10^6)	>0.01	>0.03	0				>0.01	>0.01	0.14
	Distance (m)	>29000	>29000					>59000	>59000	31000
700	Conc (m^{-2} x 10^6)	>0.06	0.09	0.22	1.01	0.65	0.89			
	Distance (m)	>29000	16000	22000	800	4000	3000			
1200	Conc (m^{-2} x 10^6)	>0.06	0.10	0.22	0.97	1.07	0.82			
	Distance (m)	>29000	14000	22000	800	1200	2600			

Shaded areas have no calculation. See text for details.
Data shown as '>' had no maximum within the range of the calculations.

were significantly wider than those of AERMOD and ISC, which were of similar width to one another, though concentrations within the ISC plume were about an order of magnitude higher. In the 700m and 1200m deep neutral boundary layers AERMOD and ADMS produced similar plume contours, ISC producing narrower plumes than either. In the two unstable boundary layer cases there was no distinction between plume contours for the two capping inversion choices in the ADMS calculations and only a small variation in the AERMOD calculations. The ISC and ADMS plume contours were very similar, the AERMOD plumes a little wider.

Values of maximum concentrations and their distances from the source, are shown in Table 8. Since most of the AERMOD calculations did not give a maximum concentration within the 30km range of the calculation, no bar chart is given of the concentration ratios against AERMOD in this section. The concentration maximum in Table 8 is at the maximum distance of the calculation where no maximum occurred within this range.

4.4 Building entrainment and plume downwash

Figures 17 to 19 show the results of single condition calculations with building entrainment and plume downwash. They are all for a 40m stack in a neutrally stable atmosphere, with the exception of one calculation for a ground-based plume source in the building wake. With the single exception of the high wind speed case in Figure 17, they are also all for the low wind speed condition. The comparison was not generally altered at the high wind speed, though relative concentrations were modified due to the reduced plume rise. In all cases the building was positioned directly downwind of the stack and its downwind extent is shown by the shaded bar on the plots.

The plots of plume centreline ground level concentration in Figure 17 show, in order, cases for:

No building and no plume entrainment or downwash (taken from Figure 5).
25m high cubical building, with limited wake entrainment and plume downwash.
35m high cubical building, with greater wake entrainment and plume downwash.
35m high cubical building, at high wind speed with more substantial wake entrainment and plume downwash.
35m high cubical building, with complete wake entrainment from a ground-based plume.
35m high, 245m wide building, with substantial wake entrainment and plume downwash.

The first five cases show the effects of increasing amounts of plume downwash and wake entrainment. The last case examines the effects of building width on plume wake entrainment and downwash and can be compared with that of the cubical building of the same height and wind speed.

The corresponding ground level concentration contour plots to Figures 17 are shown in Figure 18.

In the ground level plume centreline concentrations of Figure 17, the addition of the 25m cubical building to the dispersion calculation resulted in the maximum concentration at the ground for all three models increasing by about a factor of four. None of the models indicated any plume concentration in the immediate building wake. AERMOD and ISC calculated concentrations only from about 100m downwind of the source, with AERMOD showing a small peak and ISC showing a continual fall in concentration with increasing distance.

ADMS calculated a maximum in concentration about 200m downwind, much closer to the source than without the building (700m). Downwind of the maximum concentration, ADMS and AERMOD showed relatively similar characteristics, with ISC calculating significantly higher concentrations that the other two models.

Downwind of the larger, 35m, cubical building where wake entrainment and plume downwash were greater, ISC predicted the same concentrations as for the smaller building and AERMOD showed increased concentrations close to the building. ADMS indicated entrainment in the separation region of the building wake, with a constant concentration in this region. The concentration from ADMS then showed a sharp dip further downwind before rising to a peak of about 50% higher concentration than with the lower, 25m, building. Downwind of this peak the output of the three models was largely similar to the previous case, showing little difference due to the different sizes of building.

In the high wind speed case with the 35m building, the plume rise was reduced, which should have resulted in greater entrainment in the building wake and plume downwash. The ADMS model concentrations showed a marked increase in concentration immediately behind the building, but the following peak concentration was only slightly higher than with the low wind speed case and lower than the concentration in the immediate wake. Both AERMOD (especially) and ISC showed lower maximum concentrations at 100m distance, despite the use of normalised concentrations, which should correct for the diluting effects of altered wind speed, but not for increased concentrations resulting from the lowered plume height.

The case for zero stack height in Figure 17 produced almost identical results for AERMOD and ISC, with concentrations close to the building about an order of magnitude higher than with the elevated stacks. ADMS produced a similarly higher constant concentration immediately behind the building, followed by a continuous fall in concentration with increasing distance. However, at distances beyond about 200m its calculated concentrations were about half those from AERMOD and ISC.

The wide building calculations can be compared with those of the cubical building of the same height. The three models predicted little or no difference in the downwind maximum concentrations in each case. ADMS predicted a concentration in the wake immediately behind the wide building approximately 50% higher than that behind the 35m high cubical building, but the succeeding peak concentration was about the same, as was the subsequent fall in concentration with increasing distance.

The related ground level plume concentration contours are shown in Figure 18. ISC produced the narrowest plumes in all cases, with those of ADMS and AERMOD being more comparable with each other. At longer distances from the source, AERMOD and ISC showed little effect of the building size on the plume width. ADMS showed more variation, the widest plume occurring with the smallest building. At shorter distances the plume patterns were more complex. Neither AERMOD nor ISC should show a plume entrained immediately behind a building as this is not calculated. However, this occurred in one case, for AERMOD and the smallest building. However, this result was not repeated in the centreline concentrations of Figure 17 and was probably due to the behaviour of the contouring software on this plot. This, as noted previously, is sensitive to the grid size and the presence of sharp changes in concentration. Steps in contours in most of the other plots in Figure 18 were due to this cause. ADMS showed different contour patterns close to the building, where for all but the smallest building, the upwind edge of the plume was attached to the downwind edge of the building. In one case, for the 35m cubical building, there were two sets of contours, one set attached to the building and another set starting further down wind. The other building cases all showed discontinuities in the contour patterns near the building, partly due to contouring problems. For the wide building ADMS was the only model showing a marked increase in the plume width close to the building as would be expected in practice.

Bar charts of ratios of maximum concentration and its distance from the source for the three models are shown in Figure 19. Some distance ratios are not fixed, as the models did not produce specific maximum distances behind the buildings in all cases. The actual values and their ratios are given in Table 9; results for both low and high wind speed calculations are shown. One quarter of the concentration ratios exceeded a factor of two. ISC mostly produced higher maximum concentrations than AERMOD and usually similar or shorter distances to the maximum. ADMS and AERMOD showed more variation between each other, but overall the differences were about neutral. The greatest disparity between AERMOD and ADMS occurred with the ground-based plume, where ADMS predicted much higher maximum concentrations than AERMOD, by a factor of 3-5. This was due to the high concentrations in the entrained region in the immediate building wake produced by ADMS which were not calculated by AERMOD: at longer distances ADMS predicted lower concentrations.

It is apparent from the comparison that not only did the three models produce significantly different plume concentrations in some cases, but that there were fundamental differences between the plume concentration patterns generated by the ADMS model against the AERMOD and ISC models. These differences originate in the alternative approaches to dealing with building effects between the models.

ISC and AERMOD contain a downwash correction to plume dispersion to account for the additional turbulence and plume downwash due to buildings (Cimorelli et al(1998a)). AERMOD has largely taken the ISC procedures for this, with some limited differences in formulation. The combination of this and the different basic rates of dispersion between the models accounts for the observed differences between these two models. ISC and AERMOD do not attempt to calculate plume concentrations in the recirculating wake region immediately downwind of a building, starting the calculation just beyond this region. Further downwind, both the vertical and horizontal dispersion are adjusted, depending on the effective plume height and building sizes, resulting in both enhanced plume spreading and more rapid dispersion towards the ground, which respectively reduce and increase plume concentrations at the ground. At distances beyond ten building heights (or widths, whichever is the lesser) enhanced dispersion due to the building is fixed and with increasing distance is gradually overtaken by that due to the atmospheric turbulence.

The ADMS building entrainment model contains both a procedure for modifying plume spread and downwash and an additional procedure for dealing with plume entrainment into the recirculation region of the near wake of the building. The former is more complex and different in character to that of ISC and AERMOD and details of the whole building entrainment model are not fully explained in the CERC technical documents. The plume is partitioned into building wake entrained and unentrained fractions, dependent on the plume and building parameters. The wake entrained fraction is then set at the base of the building and entrained into the recirculating separated flow immediately behind the building, with enhanced spreading in the building wake further downwind. The unentrained fraction is left at the source height, with more limited enhancement of the plume spread. Dispersion of the two plumes is then calculated separately. The combined concentration from the merging of the two plumes is then intended to account for the combined effects of the building on the dispersing plume. The case with no building in Figure 17 shows the characteristics of the unentrained plume and the case with the ground-based plume those of the completely entrained plume. The discontinuities in the ADMS concentrations in Figure 17 were due to the summation of these two plumes, which remained relatively discrete at short distances from the building. In practice, such a sharp division in plume entrainment is unlikely to occur and the discontinuities in the downwind concentration would be heavily smoothed (as if there were a multiplicity of plume partitions).

One version of the ISC model, SCREEN, also has a model for dealing with entrainment into the recirculation region behind the building. There is also a newer building entrainment model, PRIME, intended to be used with AERMOD. Neither has been investigated in the present study as they are not formally part of the USEPA's regulatory framework (SCREEN is only intended for use in provisional studies and PRIME is relatively new).

Table 9. Maximum concentrations and their distances from the source for dispersion cases with building entrainment. (Concentrations normalised as (m^{-2}) x 10^6, (Equation 3))

Scenario	Model/Ratio	Neutral, Low wind speed		Neutral, High wind speed	
		Distance to Maximum (m)	Maximum Concentration (m^{-2} x 10^6)	Distance to Maximum (m)	Maximum Concentration (m^{-2} x 10^6)
40m stack, No building	**AERMOD**	1000	25	500	52
	ADMS	700	25	500	44
	ISC	900	50	800	60
	ADMS/AERMOD	0.70	1.01	1.00	0.85
	ISC/AERMOD	0.90	2.04	1.60	1.15
40m stack, 25m x 25m x 25m building	**AERMOD**	180	105	170	100
	ADMS	200	90	200	120
	ISC	110	250	120	190
	ADMS/AERMOD	1.11	0.82	1.18	1.19
	ISC/AERMOD	0.61	2.35	0.71	1.90
40m stack, 35m x 35m x 35m building	**AERMOD**	110	165	110	160
	ADMS	200	130	0	260
	ISC	110	250	120	190
	ADMS/AERMOD	1.82	0.76	0	1.63
	ISC/AERMOD	1.00	1.50	0.80	2.84
0m stack, 35m x 35m x 35m building	**AERMOD**	110	1100	110	800
	ADMS	0	3350	0	3820
	ISC	110	1020	110	1020
	ADMS/AERMOD	0.00	3.05	0	4.75
	ISC/AERMOD	1.00	0.93	1.00	1.27
40m stack, 245m x 35m x 35m building	**AERMOD**	110	165	110	160
	ADMS	300	140	0	150
	ISC	110	250	120	190
	ADMS/AERMOD	2.73	0.85	0	0.95
	ISC/AERMOD	1.00	1.50	1.09	1.19
AVERAGE VALUES All scenarios (5 scenarios)	**ADMS/AERMOD**	**1.27**	**1.30**	**0.44**	**1.87**
	ISC/AERMOD	**0.90**	**1.66**	**1.04**	**1.67**
With building (4 scenarios)	**ADMS/AERMOD**	**1.42**	**1.37**	**0.30**	**2.13**
	ISC/AERMOD	**0.90**	**1.57**	**0.90**	**1.80**

4.5 Annual calculations for flat terrain

Figures 20 to 22 show concentration contour maps of calculated annual concentrations for three examples of the test cases. These were for a 40m stack discharge with no buoyancy, in Figure 20, for the same stack discharge with the 35m cubical building present, in Figure 21, and for the 150m stack with a buoyant discharge, in Figure 22. Each figure shows, for each model, the annual mean concentration and the100%ile (that is, the maximum concentration), 99.9%ile and 98%ile of the calculated hourly calculations over the year. The three percentile values are in common use for regulatory purposes, along with the mean. Note that the map scales are the same for the 40m stacks, but doubled for the 150m stack in Figure 22.

The immediate impression of the three figures is that similarities between contour maps produced by the three models were somewhat limited, both in terms of the contour values and their shapes. Some broad similarities occurred, for example the distances at which the highest concentrations occurred moved in similar ways, towards the source with the addition of a building and away from the source when the discharge height was increased. Some of the variations between the contour maps are related to the behaviour of the SURFER contouring software, which all the models use. This (perhaps not surprisingly) experiences difficulties in fitting contours to grids of highly variable data, such as tend to be produced for the higher level percentiles. Thus the annual average concentration contours tended to be relatively smoothly varying plots with closed contours, while those for the higher percentiles were more erratic and showed relatively large numbers of individual peaks in the concentration contours. Also, small changes in the concentrations on the calculation grid in these cases can produce relatively large changes in the contours. However, the areas shown in the figures contained a 31 by 31 grid, which is a relatively fine resolution and the maximum useable in the ADMS model (the other models allow more grid points). Even allowing for all this, differences between the model calculations remain significant.

For the annual mean concentrations, the concentration contours for AERMOD and ADMS showed some similarities, as did the ISC model to these for the case with the building. In the other two cases the contours from the ISC model were dissimilar to the other two, especially for the higher, 150m, discharge, where the ISC model calculated less contact of the plume with the ground within the range of the calculations. Even when the contour plots appeared similar, the values and positions of their maxima could be quite variable. For the high percentile concentrations, differences between the models were greater and generally less consistent. For the cases in Figure 21, with the building, there was a broad consistency in the concentration patterns, with the models generating their highest concentrations nearer the source on the diagonal of the array grid. This behaviour was related to the cubical building being aligned with the array grid, so that its greatest cross section to the wind was presented to wind directions on the array diagonal. These wind directions should also, therefore, have produced the greatest effect on plume entrainment, moving the point of maximum concentration nearest the source and producing its highest value. This effect appeared most marked with the ADMS and AERMOD models. With the building present, the AERMOD and ISC models produced concentration maxima close to the source, while the ADMS model produced its main maxima at around 100-200m distance. These differences are related to the different downwash and entrainment procedures used, which have been described in the previous section. The ADMS model did show one unusual result with calculation with the building, which was a very high maximum value of the 100%ile, about eight times that of the other models. This occurred at a single point 1400m away at about 260° from the source. This particular maximum occurred for a wind speed of 0.5m s^{-1} and a value of 1/L of 1, a very stable boundary layer. The 100%ile plot on Figure 21 shows five such small areas with high maxima, all towards the edges of the plot.

Figure 23 shows bar charts of the ratios of distances to and values of the maximum concentrations. The actual values and their ratios are given in Table 10, for all the test cases. Differences in annual averages between the models were small for the 40m stack in isolation, but with the building present ADMS produced much increased concentrations over AERMOD. Differences between the models were distinctly greater with the higher stack discharges, where AERMOD predicted significantly higher annual mean concentrations than either ADMS or ISC. Ratios of values of the high percentile concentrations showed more variation with ADMS predicting higher concentrations overall, but not consistently. Distances to the maximum concentration showed limited variation for the annual mean values, but again much greater variation for the higher percentiles. There was no very consistent pattern in the differences. Table 10 also gives overall averages, for all the scenarios, of the concentration ratios between the models. It can be seen that, overall, ADMS predicted higher maximum concentrations than AERMOD and, with the exception of the 99.9%ile concentration, at greater distances from the source. ISC, overall, predicted similar maximum concentrations to AERMOD, but at greater distances; the maximum annual averages and 98%iles being lower and the 100%iles and 99.9%iles being higher. The largest averaged difference between these two models was 23%. For the ADMS/AERMOD comparisons, the differences were more heavily weighted by the building entrainment cases. Without these, ADMS predicted similar or lower maximum annual mean and 98%ile concentrations than AERMOD, but higher maximum values of the 100%ile and 99.9%ile. On the same basis, ISC predicted similar or lower maximum concentrations than AERMOD.

Table 10. Maximum annual mean and higher percentile concentrations for flat terrain cases. (Concentrations in mg m^{-3} for an emission of 1000g s^{-1})

Scenario	Model/Ratio	Mean		100%ile		99.9%ile		98%ile	
		Distance to Maximum (m)	Maximum Concentration (mg m^{-3})	Distance to Maximum (m)	Maximum Concentration (mg m^{-3})	Distance to Maximum (m)	Maximum Concentration (mg m^{-3})	Distance to Maximum (m)	Maximum Concentratio n (mg m^{-3})
40m stack, No buoyancy	**AERMOD**	360	0.66	100	58	140	33	280	11
	ADMS	420	0.73	100	116	100	69	280	11
	ISC	780	0.77	300	45	315	40	780	13
	ADMS/AERMOD	1.18	1.11	1.00	1.99	0.71	2.08	1.00	0.98
	ISC/AERMOD	2.17	1.16	3.00	0.77	2.24	1.19	2.76	1.18
40m stack, With buoyancy	**AERMOD**	540	0.20	200	6.3	280	4.7	420	3.0
	ADMS	540	0.23	100	12.9	220	8.4	500	3.3
	ISC	1170	0.18	1420	7.1	810	5.1	1490	3.1
	ADMS/AERMOD	1.00	1.17	0.50	2.06	0.79	1.78	1.18	1.11
	ISC/AERMOD	2.17	0.89	7.11	1.13	2.85	1.07	3.50	1.01
150m stack, No buoyancy	**AERMOD**	850	0.06	720	10.4	280	3.8	850	1.1
	ADMS	1130	0.04	200	16.8	280	8.3	1280	0.75
	ISC	1840	0.03	1200	9.9	1080	5.0	1720	0.68
	ADMS/AERMOD	1.33	0.68	0.28	1.62	1.00	2.19	1.51	0.68
	ISC/AERMOD	2.17	0.51	1.66	0.95	3.81	1.33	2.03	0.62
150m stack, With buoyancy	**AERMOD**	1650	0.008	2010	0.70	800	0.29	1440	0.15
	ADMS	2670	0.005	2060	0.44	1650	0.26	2860	0.10
	ISC	3970	0.003	1270	0.89	3970	0.21	3960	0.03
	ADMS/AERMOD	1.62	0.64	1.02	0.63	2.06	0.89	1.99	0.66
	ISC/AERMOD	2.41	0.33	0.63	1.27	4.96	0.72	2.75	0.19
40m stack, No buoyancy, 25m x 25m x 25m building	**AERMOD**	140	2.72	140	101	220	79	140	28
	ADMS	140	62	1500	690	0	154	140	62
	ISC	140	2.38	200	144	300	90	200	35
	ADMS/AERMOD	1.00	2.26	10.61	6.83	0	1.96	1.00	2.23
	ISC/AERMOD	1.00	0.88	1.41	1.43	1.34	1.14	1.41	1.24
40m stack, No buoyancy, 35m x 35m x 35m building	**AERMOD**	140	4.40	140	174	140	101	140	44
	ADMS	140	12.50	1430	1561	140	172	140	126
	ISC	140	3.77	200	220	200	158	200	45
	ADMS/AERMOD	1.00	2.84	10.12	8.97	1.00	1.70	1.00	2.85
	ISC/AERMOD	1.00	0.86	1.41	1.26	1.41	1.56	1.41	1.01
AVERAGE VALUES All scenarios (6 scenarios)	**ADMS/AERMOD**	**1.19**	**1.45**	**3.92**	**3.68**	**0.93**	**1.77**	**1.28**	**1.42**
	ISC/AERMOD	**1.82**	**0.77**	**2.54**	**1.14**	**2.77**	**1.17**	**2.31**	**0.88**
No building (4 scenarios)	**ADMS/AERMOD**	**1.28**	**0.90**	**0.70**	**1.58**	**1.14**	**1.74**	**1.42**	**0.86**
	ISC/AERMOD	**2.23**	**0.72**	**3.10**	**1.03**	**3.47**	**1.08**	**2.76**	**0.75**
With building (2 scenarios)	**ADMS/AERMOD**	**1.00**	**2.55**	**10.4**	**7.90**	**0.50**	**1.83**	**1.00**	**2.54**
	ISC/AERMOD	**1.00**	**0.87**	**1.41**	**1.35**	**1.38**	**1.35**	**1.41**	**1.13**

4.6 Effect of surface roughness on flat terrain dispersion

The choice of surface roughness is known to affect dispersion calculations, mainly via three effects. The first is the direct modification of dispersion rates by mechanical turbulence generated by the surface roughness. The second is modified wind speeds due to the changed surface roughness. The third is the effect of surface roughness on atmospheric stability; increasing roughness tends to reduce the degree of atmospheric stability and the values tend towards neutral stratification. This also directly affects predicted rates of dispersion. The effects on annual concentration calculations of the sort described above can be significant, so a brief comparison of this behaviour between the models is shown here. The annual calculations in the previous section of the report were for the quoted surface roughness of 0.1m for the Lyneham site. These were repeated using a surface roughness of 0.5m in the ADMS and AERMOD models and switching from 'rural' to 'urban' roughness in the ISC model; in this model these are the only choices available, the 'rural' surface roughness is set at 0.1m and the 'urban' surface roughness at 0.4m. The ADMS model also has an option for using an 'unrepresentative' meteorological site to the value required, where the surface roughness of the meteorological site and the calculation site are different. This was not used here, only the assumed surface roughness of the meteorological site was altered, effectively assuming that meteorological data and dispersion calculation were for the same surface roughness. The AERMOD model also requires an input of surface roughness at both the meteorological site and that of the calculation. Here, the same value of the surface roughness was used at both inputs.

Concentration contours for these calculations, for both surface roughnesses are shown in Figures 24 and 25 for a neutrally buoyant discharge at 40m height and a buoyant discharge from 150m height respectively. The plots for the surface roughness of 0.1m are the same as those shown in the previous section. For both discharge heights, ADMS and AERMOD showed a general similarity in the form of their concentration contours, both between each other and for the two surface roughnesses, though the values of the concentrations were modified. The contours from the ISC model significantly differed in appearance from the other two models at the smaller roughness, but showed a greater similarity with them when using the larger roughness.

The relative maximum concentrations and their distances are shown in the bar charts of Figure 26 and in Table 11 for each model. In all cases the higher surface roughness significantly increased the maximum annual average concentrations. The distance of this maximum from the source tended to remain constant or decrease. The maxima of the higher percentiles both increased and decreased with increased surface roughness and their distances either remained nearly static or reduced. AERMOD showed only limited changes in the distance of the maximum. Overall, ISC showed the greatest effect of changing surface roughness, both in maximum concentrations and their distances from the source. Increasing the surface roughness had either little effect on the AERMOD/ADMS relationship or reduced its differences a little. Overall, increasing surface roughness reduced the differences between AERMOD and ISC.

Table 11. Effects of surface roughness on flat terrain dispersion. (Concentrations in mg m^{-3} for an emission of 1000g s^{-1})

Scenario	Model/Ratio	Mean		100%ile		99.9%ile		98%ile	
		Distance to Maximum (m)	Maximum Concentration (mg m^{-3})	Distance to Maximum (m)	Maximum Concentration (mg m^{-3})	Distance to Maximum (m)	Maximum Concentration (mg m^{-3})	Distance to Maximum (m)	Maximum Concentration (mg m^{-3})
40m stack, No buoyancy, z_o = 0.1m	**AERMOD**	360	0.66	100	58	140	33	280	11
	ADMS	420	0.73	100	116	100	69	280	11
	ISC	780	0.77	300	45	315	40	780	13
	ADMS/AERMOD	1.18	1.11	1.00	1.99	0.71	2.08	1.00	0.98
	ISC/AERMOD	2.17	1.16	3.00	0.77	2.24	1.19	2.76	1.18
40m stack, No buoyancy, z_o = 0.5m	**AERMOD**	360	1.05	100	56	140	32	280	11
	ADMS	280	1.08	100	100	100	63	280	11
	ISC	280	2.02	200	62	140	55	220	24
	ADMS/AERMOD	0.78	1.03	1.00	1.79	0.71	1.99	1.00	0.98
	ISC/AERMOD	0.78	1.92	2.00	1.11	1.00	1.74	0.79	2.16
150m stack, With buoyancy, z_o = 0.1m	**AERMOD**	1650	0.008	2010	0.70	800	0.29	1440	0.15
	ADMS	2670	0.005	2060	0.44	1650	0.26	2860	0.10
	ISC	3970	0.003	1270	0.89	3970	0.21	3960	0.03
	ADMS/AERMOD	1.62	0.64	1.02	0.63	2.06	0.89	1.99	0.66
	ISC/AERMOD	2.41	0.33	0.63	1.27	4.96	0.72	2.75	0.19
150m stack, With buoyancy, Z_o = 0.5m	**AERMOD**	1460	0.01	2280	0.59	900	0.29	1410	0.18
	ADMS	2090	0.009	1900	0.43	1560	0.27	2040	0.15
	ISC	1400	0.02	1280	0.67	2780	0.48	1840	0.30
	ADMS/AERMOD	1.43	0.90	0.83	0.73	1.73	0.92	1.45	0.85
	ISC/AERMOD	0.96	2.40	0.56	1.14	3.09	1.66	1.30	1.67
AVERAGE VALUES (4 scenarios)	**ADMS/AERMOD**	1.25	0.92	0.96	1.28	1.31	1.47	1.36	0.87
	ISC/AERMOD	1.58	1.46	1.55	1.07	2.82	1.33	1.90	1.30

4.7 Dispersion over terrain

4.7.1 Single condition calculations in neutral stability

Figure 27 shows ground level plume centreline concentrations for the three models over all the terrains in neutral stability. All cases used a 40m discharge height, low wind speed and no buoyancy in the discharge. The cases with no terrain, from Figure 5, and with the gaussian hill are included. The position of the stack is marked and is at the left axis of the plot except for case 6, where the stack was on the terrain (and the distance scale was doubled). Values of the maximum concentrations and their distances from the source are given in Table 12.

Without terrain, the maximum concentrations occurred between 700m and 1000m downstream and the centreline concentrations followed a smooth curve. Except in case 3, the plume reached the terrain before the maximum concentration at the ground would have occurred over flat terrain. The concentration distribution on the plume centreline was clearly influenced by the terrain. All the models showed some increase in ground level concentration due to its overall effect; the plume centreline concentrations showed additional local effects, increasing concentrations where the terrain slopes increased and reducing concentrations where they decreased.

For cases 3 and 4, respectively the farthest and smallest terrains, AERMOD showed quite limited effects due to the terrain and dispersion was similar to the case without terrain, though locally perturbed. For the farthest terrain (case 3) the AERMOD plume reached an initial local maximum ground level concentration in front of the terrain, similar to that without the terrain. However, a further, slightly higher, concentration occurred over the highest terrain peak. ADMS showed a small reduction in the maximum concentration in case 3, presumably due to the plume experiencing some slight uplift ahead of the terrain, where the maximum occurred. In case 4, where the terrain gradients were shallow, only a small deflection of the mean streamline would have occurred, with a consequently small effect on the predicted concentration. ISC showed relatively larger increases in concentration over both of these terrains.

All the models showed significant effects due to the other terrains. ADMS generally showing the smallest increases in plume concentration at the ground and ISC the largest. However, except for cases 5 and 6 the essential differences between the models in flat terrain were retained. The concentration distributions followed the same pattern as in flat terrain with an additional perturbation generated by the terrain. In case 5, the steepest terrain, and case 6, the most extensive terrain with the discharge stack on the upwind slope, the effects were sufficiently marked to dominate the concentration distributions and the differences between the models were altered.

For AERMOD, the effect of the local terrain height on the centreline values can clearly be seen in the differences in dispersion between cases 1, 4 and 5 and for the gaussian hill, which produced greater concentration maxima over the terrain peaks and hence closest to the source. For case 6, the larger scale of the calculation grid led to a smoother concentration profile because data can only be output at the resolution of this grid. There was however, a much higher peak concentration compared with cases 1 to 5 and this occurred much closer to the source. The main effect of terrain in the AERMOD model in case 6 is that the potential temperature gradient is non-zero below the mixing height for neutral and stable boundary layers (that is, with $L_{mo}>0$). As described in Appendix 1, this resulted in a critical dividing streamline height, forcing more of the plume to spread around the hill rather than rising over it. This meant that the horizontal plume component of the terrain correction (Equation e3 in Appendix 1) became more important and this is terrain dependent because the concentrations are calculated at local terrain heights. For case 6 the local terrain heights were significant close to the source relative to the effective source height and this led to a large concentration contribution (Equation e2 in Appendix 1).

For ADMS, the centreline plots for the neutrally stable boundary layer typically showed concentrations a factor of 1.5 higher at the ground due to the terrain. The exceptions were cases 3 and 4, discussed above. When compared to AERMOD, the ADMS concentrations were lower and the maximum values occurred at a greater distance downstream. The terrain following variations in the modelled mean concentration can be seen from the centreline plots and these show that the maximum concentrations occurred over the first terrain peak with AERMOD and over the second, slightly larger peak with ADMS. It would thus appear that the local terrain structure could strongly influence the position of the maximum as well as its value.

The ADMS results for case 6 were consistent with the corresponding cases 1,2,4 and 5. Since FLOWSTAR (the ADMS wind field model) depends on terrain gradients, there would be differences in the concentration profiles between cases 2 and 5, where the profile gradients were doubled. The differences between case 2 and case 6, where the profile gradients were the same, resulted from the closer proximity of the source to the terrain in case 6. In AERMOD there is no wind field calculation and terrain enters the concentration calculation only via its height relative to that of the stack. However, for case 6 the proximity of the source to the terrain appeared to dominate the concentration calculation in AERMOD, resulting in much higher concentrations than with ADMS.

For ISC, the predicted maximum without terrain was about twice that of the AERMOD prediction. With terrain the differences between the maxima increased significantly. The highest values were over the highest terrain or where the source was close to the terrain, the distances to maximum concentration generally falling between those of AERMOD and ADMS. For case 6, the maximum predicted concentration was also larger than for ADMS, but downstream distributions were similar. The possible loss of terrain following detail in this case, because of the reduced resolution of the output grid, applied to all three models.

4.7.2 Single condition calculations in unstable boundary layers

Figure 28 shows plume centreline concentrations in neutral, stable and unstable boundary layers for terrain Cases 2 and 5. The neutral stability cases are those from Figure 27. Values of the maximum concentrations and their distances from the source are also given in Table 12 for all the cases.

In the unstable boundary layer all the models showed a reduction in the effect of the terrain. With the exception of case 6, the AERMOD model plume centreline concentrations showed no significant effect from the presence of terrain. The maximum concentrations agreed to within ±1% with the equivalent case without terrain and the distances to the maximum concentrations were the same, within the resolution of the output grid, which had a spacing of 100m for cases 1-5. The peak concentrations probably actually occurred between 200m and 300m from the source, which was just upwind of the terrain, but this distance was not resolved within the 100m grid spacing of the calculation. This has some implications for the comparison of maximum ground level centreline concentrations with the other models.

For case 6, AERMOD still predicted a maximum 300m downwind of the source, which was in this case on the upwind slope of the hill. However, as with the other models, the shape of the centreline profile did not show any local terrain dependency. The contribution of the flagpole receptor in this case is not the same as in the terrain following part close to the source, since the stack is located on terrain. Hence the concentration is reduced. The reason for this is covered in more detail in Appendix 1.

Table 12 shows the maximum concentration predicted by ADMS for the 40m stack with a non-buoyant discharge without terrain to be approximately 1.9 times the AERMOD equivalent for all the terrain cases. Also, all the ADMS maximum concentration calculations over terrain were within ±7% of those without terrain (except for case 6, which was within 10%). This limited effect of terrain in unstable boundary layers is due to the nature of the ADMS model's treatment of convective boundary layers. It is covered in more detail in Appendix 1.

The maximum concentration predicted by ISC was between 1.5 and 2 times that of AERMOD without terrain (except for case 6, which is considered below). This was less than the equivalent ADMS/AERMOD ratio and this pattern was maintained for terrain cases 2-5. There was slightly more variation in the distance at which the maximum concentration occurred but this may have had more to do with interpolation between the calculation grid than with the dispersion calculation per se. This can be explained by the fact that, for cases 1-4, most receptor points were below the stack release height and were therefore modelled in ISC as simple (flat) terrain. Only a few points, for which the terrain height was greater than the stack height but less than the plume height, were classed as intermediate terrain. In this situation, concentrations both with and without terrain (Equation i2 in Appendix 1) were calculated and the higher of the two values adopted.

For case 6 in particular (and to some extent case 1), receptors relatively close to the source, where the maximum concentration was expected to occur, were in the intermediate terrain class. Indeed, some receptor points may have been above the effective plume height. These were complex terrain receptors. However, it is the relative importance of the terrain height compared with the plume rise in the vertical component of both equations i1 and i2 (in Appendix 1) which mainly affects concentration. This also explains the smaller predicted maximum concentration for case 5, where the terrain had the same peak height as case 6 but at a greater distance from the source. It should be noted that ISC predicted a much increased maximum concentration for case 6 due to the terrain, while AERMOD and ADMS both predicted similar concentrations to those without terrain.

4.7.3 Single condition calculations in stable boundary layers

In the stable boundary layer, without terrain, the centreline ground level concentrations predicted by AERMOD were still increasing at the downstream limit of the model domain and did not give significant concentrations at the ground until about 1200m from the source. For terrain cases 1,2,4 and 5, this would have been almost completely downstream of the terrain. In practice, for all the terrain cases the concentration profiles were distinctly terrain following, as with the neutrally stable boundary layer. The maximum concentrations occurred over the terrain and were larger than without terrain or than their neutrally stable equivalents. In all cases the concentration reduced rapidly in the lee of the terrain and then increased again, following the same pattern as without terrain. This is because, in the AERMOD model, the terrain heights do not influence the concentration calculation at any flat terrain location in the vicinity of the hill, so the calculation at the given grid point is as if there were no terrain upwind of it.

The main differences in the meteorology between the neutral and stable cases that affected the concentration calculations were the Monin-Obukhov length scale and the boundary layer height. The stable atmosphere of the present calculation for AERMOD used values of $1/L_{mo}$=0.01 and Z_{im}=200m (compared with $1/L_{mo}$=0.004 and Z_{im}= 375m for the neutrally stable boundary layer). The increased $1/L_{mo}$ gave a greater buoyancy frequency and hence a larger critical dividing streamline height at each receptor. The receptor height scales were themselves independent of stability. It would appear from the terrain following nature of the centreline concentration profiles that the horizontal plume component dominated in the calculation. In this component the terrain heights enter directly in the vertical term of equation e2 (in Appendix 1). The flagpole receptors give greater values at a given (x,y) position compared to the ground level values. Hence the maximum values of concentration were larger over terrain than without. When the terrain height was less than half of the plume height (as in case 4), the flagpole receptor contribution rapidly reduced. The increased weighting of the horizontal plume component in stable conditions compared with neutral conditions explains the increased concentrations. The large maximum concentration predicted for case 6 can be explained in the same way as the neutral result. The terrain influence which is seen in the downstream profile results from the increased dominance of the horizontal plume component as described above.

The maximum centreline concentration for ADMS under stable conditions without terrain was approximately 2.4 times that for AERMOD and occurred closer to the source. In terrain cases 1,2,3 and 6, the ADMS centreline concentrations were lower than for AERMOD (by approximately 70% for cases 1 to 3 and by 95% for case 6) whereas for case 4 they were greater. In case 5, the maximum concentrations for ADMS and AERMOD were similar but the profiles differed downwind. The maxima also generally occurred further downstream for ADMS compared with AERMOD. The multiple peaks in the terrain profiles made the position of the maximum concentration more variable. Under stable conditions, both AERMOD and ADMS predicted a higher concentration over the second peak (except for AERMOD in case 6), though in the neutrally stable boundary layer the AERMOD model's maxima were over the first peak.

In the stable boundary layer the presence of terrain increased the ADMS model's concentration maxima by factors between 1.5 and 3.3, and these occurred closer to the source. Concentrations were lower than the equivalent values in neutral stability and occurred further downstream. They also showed the same multiple peaks in the centreline concentration profile but with the higher peak further downstream. The second maximum occurred over a small third peak in the terrain which can be seen on the centreline profile plots.

ADMS uses the same formula to calculate concentrations in both stable and neutral conditions as defined here. For flat terrain, the main differences are in the boundary layer parameters such as U, σ_y and σ_z, which depend on L_{mo} (and on N, the Brunt-Vaisala frequency). The vertical plume spread was smaller under stable conditions, compared with the neutral, while the lateral plume spreads were very similar. With the stable boundary layer over terrain the mean plume centreline was closer to the ground for longer. This downward deflection of the plume resulted in higher concentrations closer to the source. Despite this, concentrations for cases 1-6 were still lower than their equivalents in the neutrally stable boundary layer, ($C_{stable}/C_{neutral} \cong 0.8$) but the difference was less than that without the terrain ($\cong$0.4). Hence stability as well as terrain influenced concentration predictions. These combined effects of stability and terrain were also responsible for the relative differences in the concentrations along the plume centreline. The FLOWSTAR wind field perturbations, which determine the deflection of the mean streamline used in the dispersion calculations in ADMS, depend on terrain gradient and, as a result, the highest concentrations were predicted over the steepest parts of the terrain.

Without terrain, the ground level concentration predicted by ISC in the stable atmosphere continued to increase with distance to the limit of the model domain. The maximum concentration was approximately six times that from AERMOD, occurring at the same point. For terrain cases 1-6, the peak concentrations from ISC varied from 3 to 27 times the value without terrain. Concentrations were generally less than the equivalent values for neutral stability (except for case 6), but greater than predicted by either ADMS or AERMOD due to the terrain (between 3 and 9 times the values for AERMOD). The proximity of the source to the terrain and the height of the terrain relative to the effective height of the plume were the most important factors in ISC determining the concentration. Thus cases 1 and 6 showed the highest peak concentrations for all stabilities.

As the stable boundary layer was classed as 'E' stability, the effective source height (equation i3 in Appendix 1) was lower than in the neutrally stable case as the plume rise was reduced. Hence most points in the ISC calculation fell in the intermediate or complex terrain category. The centreline plots for stable (and neutral) boundary layers appeared to show a change in the shape of the concentration profile over terrain where the calculation method changed from simple to complex terrain and the effect of the terrain shape on the concentration pattern can be clearly seen.

4.7.4 Concentration contours for all stabilities

Figures 29, 30, and 31 show concentration contour maps matching the plume centreline concentration plots on Figures 27 and 28. Figure 29 shows results for neutral stability, Figure 30 for all stabilities in case 2 and Figure 31 for all stabilities in case 5. Only the outer boundaries of the terrain are shown, with the terrain area shaded in order to avoid a confusion of contours.

In neutral stability, Figure 29, the concentration contours for AERMOD showed a reduced lateral plume spread and greatly increased local concentration due to the terrain, although the plume rapidly readjusted to the same state as without terrain further downstream. The plume narrowing over the terrain was more pronounced for cases 5 and 6 and in case 5 the plume also showed some asymmetry. The ISC model plumes were narrower than those from AERMOD, both with and without terrain. Unlike AERMOD and ISC, the ADMS plumes were symmetrical, irrespective of the form of the terrain. There was also a widening of the plume over the terrain and the concentration contours showed the effect of the change in terrain elevation on and around the plume axis. This was the opposite effect to that displayed by AERMOD.

The marked differences in the plume contours between unstable and stable boundary layers are clearly apparent in Figures 30 and 31. The stable plumes from ADMS were generally wider than their AERMOD equivalents and the same contours extended further downstream. They also widened over the terrain, rather than narrowing. The plume narrowing and increased concentration over the terrain produced by AERMOD in stable stratification was more extreme than under neutral conditions. A distinct double-peaked structure was observed in the concentration contours over the terrain and in its wake. For ISC, the change in the calculation method from 'simple' to 'complex' terrain and the effect of the terrain shape can also clearly be seen with localised high concentrations over the terrain peaks in neutral and stable conditions compared with unstable. The ISC plumes were wider than from AERMOD (except in case 6) but narrower than from ADMS. They also widened over the terrain. The blunt upwind edge of the plume contours was due to the sector-averaging processing procedure used in this model.

In the unstable boundary layer, ADMS and AERMOD showed similar spreads and the plume width was not affected by the terrain in either model, as it was for ISC. In ISC, the plumes showed similar spreads to AERMOD and ADMS for cases 1-4, with the plume narrowing over the terrain in cases 5 and 6.

The bar charts of Figure 32 show the relationships between the models' maximum concentrations and distances for all the terrain cases. Overall, ADMS produced lower maximum concentrations than AERMOD in the neutrally stable boundary layer, much lower concentrations in the stable boundary layer and higher concentrations in the unstable boundary layer. ISC persistently produced higher maximum concentrations than AERMOD in all cases. Distances to the maximum concentration showed rather less variation than the maxima themselves. These mostly showed limited variation between the models and no very consistent pattern. The greatest differences occurred between ADMS and AERMOD, where ADMS mostly produced longer distances to the maximum in the neutral and stable boundary layers and shorter distances in the unstable boundary layer.

Table 12. Effects of terrain on single condition releases. (Concentrations normalised as $(m^{-2}) \times 10^6$ (Equation 3))

Scenario	Model/Ratio	Neutral		Unstable		Stable	
		Distance to Maximum (m)	Maximum Concentration ($m^{-2} \times 10^6$)	Distance to Maximum (m)	Maximum Concentration ($m^{-2} \times 10^6$)	Distance to Maximum (m)	Maximum Concentration ($m^{-2} \times 10^6$)
No terrain	**AERMOD**	1000	24.4	300	38.9	1600*	4.00
	ADMS	700	24.9	200	75.3	1400	9.50
	ISC	900	47.7	300	60.1	1600*	23.2
	ADMS/AERMOD	0.7	1.0	0.7	1.9	*	*
	ISC/AERMOD	0.9	2.0	1.0	1.5	*	*
Gaussian Hill	**AERMOD**	500	71.9	300	38.7	500	98.8
	ADMS	600	36.6	200	79.7	700	13.0
	ISC	500	426.0	300	83.8	600	325.0
	ADMS/AERMOD	1.2	0.5	0.7	2.1	1.4	0.1
	ISC/AERMOD	1.0	5.9	1.0	2.1	1.2	3.3
Case 1	**AERMOD**	500	58.3	300	38.7	800	64.6
	ADMS	700	39.1	200	70.2	1100	21.2
	ISC	500	301.0	400	79.1	700	255.0
	ADMS/AERMOD	1.4	0.7	0.7	1.8	1.4	0.3
	ISC/AERMOD	1.0	5.2	1.3	2.0	0.9	4.0
Case 2	**AERMOD**	700	41.7	300	38.9	900	75.6
	ADMS	900	30.3	400	70.2	1000	19.6
	ISC	700	188.0	300	61.0	900	180.0
	ADMS/AERMOD	1.3	0.7	1.3	1.8	1.1	0.3
	ISC/AERMOD	1.0	4.5	1.0	1.6	1.0	2.4
Case 3	**AERMOD**	1300	25.0	300	38.9	1300	43.4
	ADMS	1300	19.3	200	75.7	1300	15.9
	ISC	1300	86.3	100	60.1	1100	87.8
	ADMS/AERMOD	1.0	0.8	0.7	2.0	1.0	0.4
	ISC/AERMOD	1.0	3.5	0.3	1.5	0.9	2.0
Case 4	**AERMOD**	900	26.0	300	38.9	900	7.30
	ADMS	900	26.4	200	75.6	1300	14.3
	ISC	700	109.0	300	60.4	900	67.3
	ADMS/AERMOD	1.0	1.0	0.7	1.9	1.4	2.0
	ISC/AERMOD	0.8	4.2	1.0	1.6	1.0	9.2
Case 5	**AERMOD**	600	37.2	300	38.9	800	34.0
	ADMS	900	37.0	200	76.0	900	31.4
	ISC	600	198.0	300	61.6	600	106.0
	ADMS/AERMOD	1.5	1.0	0.7	2.0	1.1	0.9
	ISC/AERMOD	1.0	5.3	1.0	1.6	0.8	3.1
Case 6	**AERMOD**	300	158.9	300	31.5	300	209.3
	ADMS	700	38.9	300	68.0	700	22.2
	ISC	500	384.2	300	155.6	300	623.5
	ADMS/AERMOD	2.3	0.2	1.0	2.2	2.3	0.1
	ISC/AERMOD	1.7	2.4	1.0	4.9	1.0	3.0
AVERAGE VALUES All scenarios (8 cases)	**ADMS/AERMOD**	**1.3**	**0.7**	**0.8**	**2.0**	**N/A**	**N/A**
	ISC/AERMOD	**1.0**	**4.1**	**1.0**	**2.1**	**N/A**	**N/A**
Terrain scenarios (7 cases)	**ADMS/AERMOD**	**1.4**	**0.7**	**0.8**	**2.0**	**1.4**	**0.6**
	ISC/AERMOD	**1.1**	**4.4**	**0.9**	**2.2**	**1.0**	**3.9**

* Maximum was beyond the range of the calculation, so no ratio is given.

4.7.5 Annual calculations

Calculations of annual statistics were made for the six terrains used here. Plotted examples of three terrain cases are shown here. Figure 33 gives contour concentration plots of annual average and 99.9%ile concentrations for the three models for the 40m height discharge, without terrain, and Figures 34, 35 and 36 give the same results over terrain cases 2, 5 and 6. These are reasonably representative of the whole.

The plots without terrain are the same as those of Figure 20, repeated at the same scale as the following terrain cases. Figure 37 gives bar charts of the maxima of the statistical parameters and their distances, which are also detailed in Table 13. As in Figures 29-31, only the outer boundary of the terrain is marked and the area inside it is shaded. The contour concentrations are in mg m^{-3} for a discharge of 1000g s^{-1}.

For the annual statistical calculations the terrain grid was set at 160m spacing for ADMS and the output grid spacing at 100m. These larger grid sizes were needed in order to calculate concentrations in all directions from the source and not just in the single wind direction over the terrain, as in previous calculations shown here. For AERMOD and ISC, terrain data was interpolated onto the 100m receptor grid from the 40m grid spacing of the terrain data file.

The figures show that, for ADMS, the annual average concentrations for cases 2 and 5 (as well as for the other cases, 1,3,4 and 6, not shown in the Figures) were similar and largely unaffected by the terrain; the only difference was in case 6, in which it was 12% higher than without terrain. The maxima were also mostly close to the stack, suggesting that these were dominated by unstable atmospheres. Previous calculations here have shown that the highest concentrations occurred under unstable conditions, and for the test cases used in this study, with the exception of cases 1 and 6, this would occur before the plume reached the terrain. The loss of terrain grid resolution in the annual calculations would also further reduce the effects of the terrain on the model results. The same pattern is also seen in the percentile predictions. The 99.9%ile plots and the other high percentile values Table 13 indicate that maximum concentrations were mostly very similar to the values without terrain and occurred in the same approximate location. The main differences were in case 6, where the source was located on the terrain.

The AERMOD results showed a similar overall distribution to the corresponding results without terrain but with higher concentrations predicted over the terrain. The maximum annual average concentrations and percentile predictions occurred on the terrain, except forcase 3 (the farthest source), where no effect of terrain was apparent in either the 98%iles or in the annual means, and case 4 (the lowest terrain) for which no effect of terrain was seen. For cases 5 and 6, the absolute height of the terrain is greatest and the highest concentrations were predicted. For ADMS, the highest concentrations for all the statistics except the 99.9%ile occurred in case 6, where the source was located on the terrain, but were significantly greater for AERMOD (for example 2.2 times the annual mean without terrain, compared with 1.1 for ADMS). For the other cases, when the AERMOD results showed the influence of the terrain, the predictions of the two models differed particularly over the locality of the maxima. However, for AERMOD (again with the exception of case 6), it is possible to obtain hourly concentrations on flat terrain which are comparable to those predicted over terrain for the different stability conditions occurring over the year. This is reflected in the fact that away from the terrain the 98%ile and annual mean contour plots for ADMS and AERMOD were quite similar.

Table 13. Effects of terrain on annual statistics. 40m discharge height, no buoyancy. (Concentrations in mg m^{-3} for 1000g s^{-1} discharge)

Scenario	Model/Ratio	Mean		100%ile		99.9%ile		98%ile	
		Distance to Maximum (m)	Maximum Concentration (mg m^{-3})	Distance to Maximum (m)	Maximum Concentration (mg m^{-3})	Distance to Maximum (m)	Maximum Concentration (mg m^{-3})	Distance to Maximum (m)	Maximum Concentration (mg m^{-3})
No terrain	**AERMOD**	360	0.7	100	57	140	33	280	11
	ADMS	420	0.7	100	116	100	69	280	11
	ISC	780	0.8	300	45	320	40	780	13
	ADMS/AERMOD	1.2	1.0	1.0	2.0	0.7	2.2	1.0	1.0
	ISC/AERMOD	2.2	1.1	3.0	0.8	2.3	1.2	2.8	1.2
Case 1	**AERMOD**	500	1.2	580	157	580	88	500	13
	ADMS	420	0.7	100	114	140	55	280	10
	ISC	500	4.2	610	346	580	267	400	61
	ADMS/AERMOD	0.8	0.6	0.2	0.7	0.2	0.6	0.6	0.8
	ISC/AERMOD	1.0	3.5	1.1	2.2	1.0	3.0	0.8	4.7
Case 2	**AERMOD**	670	0.8	620	91	620	65	280	11
	ADMS	420	0.7	100	115	140	55	280	10
	ISC	670	2.1	600	274	600	110	580	36
	ADMS/AERMOD	0.6	0.9	0.2	1.3	0.2	0.8	1.0	0.9
	ISC/AERMOD	1.0	2.6	1.0	3.0	1.0	1.7	2.1	3.3
Case 3	**AERMOD**	360	0.7	1140	88	1140	44	280	11
	ADMS	420	0.7	100	115	140	55	280	10
	ISC	950	1.2	1120	196	1120	77	950	19
	ADMS/AERMOD	1.2	1.0	0.1	1.3	0.1	1.3	1.0	0.9
	ISC/AERMOD	2.6	1.7	1.0	2.2	1.0	1.8	3.4	1.7
Case 4	**AERMOD**	360	0.7	100	57	140	33	280	11
	ADMS	420	0.7	100	115	140	55	280	10
	ISC	670	1.2	500	71	410	47	580	21
	ADMS/AERMOD	1.2	1.0	1.0	2.0	1.0	1.7	1.0	0.9
	ISC/AERMOD	1.9	1.7	5.0	1.2	2.9	1.4	2.1	1.9
Case 5	**AERMOD**	580	1.2	920	580	630	142	580	11
	ADMS	420	0.7	100	114	140	55	280	10
	ISC	580	4.9	500	713	580	390	410	48
	ADMS/AERMOD	0.7	0.6	0.1	0.2	0.2	0.4	0.5	0.9
	ISC/AERMOD	1.0	4.1	0.5	1.2	0.9	2.7	0.7	4.4
Case 6	**AERMOD**	320	3.2	500	1164	220	524	280	24
	ADMS	470	0.8	110	134	120	59	330	11
	ISC	220	8.8	500	674	220	523	200	149
	ADMS/AERMOD	1.5	0.3	0.2	0.1	0.5	0.1	1.2	0.5
	ISC/AERMOD	0.7	2.8	1.0	0.6	1.0	1.0	0.7	6.2
AVERAGE VALUES All scenarios (7 scenarios)	**ADMS/AERMOD**	1.0	0.8	0.4	1.1	0.4	1.0	0.9	0.8
	ISC/AERMOD	1.5	2.5	1.8	1.6	1.4	1.8	1.8	3.3
Terrain runs (6 scenarios)	**ADMS/AERMOD**	1.0	0.7	0.3	0.9	0.4	0.8	0.9	0.8
	ISC/AERMOD	1.4	2.7	1.6	1.7	1.3	1.9	1.6	3.7

The effect of the terrain can also be seen for ISC in all cases 1 to 6. The concentrations followed roughly the same trend as AERMOD, in that higher concentrations were calculated when the terrain height was greater (in cases 5 and 6) or when the source was close to the terrain (in case 1). However, higher maximum concentrations were predicted by ISC than with AERMOD and the 98%iles also showed the effect of the terrain. This is consistent with the single condition calculations for ISC, which showed that higher concentrations occurred over terrain in neutral and stable boundary layers rather than unstable. These were considerably higher than for the other models and for the case without terrain. Away from the terrain the contour patterns rapidly become similar to the case without terrain for all long term statistics.

All the models also showed very low concentrations in a 30° sector for winds from the ESE, both with and without terrain. This was a facet of the prevailing meteorology and not an effect induced by the terrain.

4.7.6 Effect of variable terrain and output grid sizes

It was noted in section 3.8 that the choice of receptor, output and (in the case of ADMS) terrain grid scales can significantly affect the dispersion calculation. This was investigated briefly using case 2 under stable conditions only.

For the standard calculations a terrain grid spacing of 40m and an output grid spacing of 100m were used, except in case 6 where the spacing was doubled in line with the expanded scale of the terrain and the calculation area. Hence it was decided to test the effect on output concentration of the combination of:

> firstly, the standard terrain grid (40m) with a coarse output grid (200m) for AERMOD,
> secondly, the coarse terrain grid (80m) with the coarse output grid (200m) for ADMS only and,
>
> finally, the coarse terrain grid (80m) with the standard output grid (100m) for both AERMOD and ADMS.

Case 2 was used in the sensitivity analysis as a representative standard example from the full set of terrain cases. Stable conditions were selected since the concentration profiles were seen to be most strongly affected by terrain under these conditions. No data are presented in the report but the findings are briefly outlined below.

In AERMOD, the terrain grid is interpolated onto the required output grid before any calculation is performed. Hence, when the output grid spacing is doubled the model predictions should agree at those points on the coarser (200m) grid which are also contained in the original (100m) grid. This was found to be the case. However, since the resolution of the grid was reduced, the coarser grid might not provide such accurate interpolated output; at the point of maximum concentration on the original grid for example. This was seen to change the position of the predicted maximum as well as reducing its magnitude, by approximately 30% in the test case. It can be expected that normally AERMOD will use terrain data at the resolution provided by the OS (usually between 30m and 50m). It is instructive to examine the effect of initially using terrain data at a coarser (80m) resolution, interpolated onto the standard (100m) calculation grid, since this preserves the shape of the centreline terrain profile. However, it reduced the predicted maximum concentration by about 50%. In both cases the terrain resolution was smaller than the output grid resolution and the terrain heights used in the concentration calculations would not therefore differ significantly. However, the receptor height scales may be quite different.

Again, for ADMS, it appeared that when the terrain grid was less detailed (80m) and the dispersion output grid was comparable with this (100m) then loss of terrain information led to a slight reduction in the predicted concentrations (approximately 15% of the maximum value) but the shape of the centreline concentration profile was maintained. If the coarser (80m) terrain grid was used with a 200m dispersion output grid spacing, then the interpolation onto the output grid resulted in a concentration profile which was similar to the case without terrain. The difference in the peak concentration between the two output grid sizes (100m and 200m) for the 80m terrain grid was of the order of 60%.

4.8 Discussion of dispersion intercomparison

Most detailed aspects of this intercomparison have already been considered in the individual sub-sections here or in the relevant Appendices, so the present discussion will mainly consider its wider aspects.

Differences between the three models in the single condition calculations have, overall, been smallest in neutrally stable boundary layers and with the lowest plume height, increasing with both plume height and in stable or unstable boundary layers.

In the comparison of basic rates of dispersion and plume rise, AERMOD and ADMS showed relatively small differences in predicted maximum concentrations (of the order of 10-20%) for the low, 40m, stack discharge in the neutrally stable boundary layers. With increasing stack height or non-neutral stability, differences between these two models generally increased markedly, approaching or surpassing a factor of two in most cases. Stable boundary layers generally produced greater differences than unstable. The ISC model showed significantly greater differences in predicted concentrations from the other two models, except for the low discharge stack in the high wind speed neutrally buoyant boundary layer, where it was largely similar. Overall it produced the narrowest plumes. Relative distances to the maximum concentration also varied considerably between the models.

Increasing the stable boundary layer height to 200m for all the dispersion calculations altered concentrations at the ground with the ADMS model, but not so greatly as to affect the conclusions of the intercomparison.

Overall, the older ISC model showed more marked differences in its behaviour from the AERMOD and ADMS models, which tended to show relatively similar behaviour to each other, though often with quite variable differences in predicted concentrations. One of the features of the newer models was a more marked reaction to non-neutral stability. There was a more rapid dispersion of plumes to the ground in unstable boundary layers and slower rates of dispersion in stable boundary layers. One result of the latter behaviour is the tendency of the higher plumes (due either to source height or plume rise) in stable boundary layers to remain above the ground for significantly greater distances than predicted by ISC. In many cases the present calculations have indicated little or no contact of plumes with the ground within the 30km range of the calculations. Beyond distances of this order it is arguable whether these models remain reliable, as the weather pattern and Coriolis effects (lateral wind shear and curving plume paths) start to have a major effect on dispersion. This is a marked feature of the dispersion calculations considering the relatively modest stability of the test case used here (equivalent to a Pasquill/Gifford category E).

There is often a tendency for annual calculations to smooth out larger variations in single state calculations, but in the examples studied here this does not seem to have been particularly the case. Differences between the three models in annual average calculations in flat terrain were again relatively small for the lowest stack, but showed more marked differences for the taller stack or with the inclusion of buildings. Differences between the higher percentiles also increased. All the models reacted in a similar way to increased surface roughness, maintaining the differences between them.

The investigation of boundary layer/buoyant plume interactions showed substantial differences between the models in stable and neutrally stable boundary layers. The models all behaved differently in describing plume interaction with the top of the boundary layer, though ISC departed more markedly from the behaviour of the other two models. In particular there were order of magnitude differences between predicted concentrations at the ground in the shallow, 200m deep, stable boundary layer, where only the ISC model reached a maximum concentration within the 30km range of the calculation. AERMOD and ADMS also showed variable amounts of the plume reflected at the top of the boundary layer in these cases. ADMS also showed little variation in concentration at the ground for stable boundary layer heights of 90m and 200m, above and below the 150m stack used. In unstable boundary layers differences between the models were smaller at longer ranges and to some extent explainable in terms of the varying boundary layer depth. It appeared that with the two deeper boundary layers the plume interaction with the top of the boundary layer was either of no significance to the calculation or resulted in near total reflection in all cases. The concentration maxima were similar for the three models, but marked differences in their distances resulted in large differences in concentrations at shorter ranges.

None of the models was effective at estimating near-field building plume downwash and entrainment. The AERMOD and ISC models did not attempt to calculate in this region. ADMS calculates a concentration in the building wake from an entrained fraction of the plume, followed by a two-part calculation of the entrained and unentrained fractions. However, the dichotomous nature of the partition makes the calculation unreliable until the two parts of the plume are reasonably well merged, which did not occur here until the same order of distance as the start point of the AERMOD and ISC calculations. None of the models deals very effectively with multiple buildings or those of complex shapes, using only the effective bulk cross sections of the structures. Though this may be a plausible (though uncertain) assumption for far field calculations, it ignores too many of the more important localised building entrainment effects to be reliable in the near field. In the far field the models behaved more similarly, though predicted concentrations remained significantly different. The more recently available PRIME building entrainment model (not included in this study), which is intended as an enhancement to the AERMOD model, contains a more complex procedure than at present used by AERMOD and may improve its treatment of building entrainment effects.

All the models produced changes in dispersion patterns over the terrain used here, except for terrain cases 3 and 4, which were intended to be (and were) at the margins of any effects. The greatest effects were in neutrally stable and stable boundary layers, unstable boundary layers showing almost no significant effects of the terrain in most cases. The stable boundary layer cases also produced the largest differences between the models. ISC generally produced by far the greatest reaction to the terrain, and the highest concentrations over it. There are fundamental differences in the calculation procedures between AERMOD and ADMS. AERMOD uses a (complex) empirical correction for the effects of the terrain and ADMS calculates a full wind field and a modified dispersion based on it. Considering this, it is surprising that the differences between the two models' calculated concentrations were so relatively small. The most significant differences occurred when the stack was actually located on the terrain (case 6), not on the flat away from the terrain. In this case, under neutral conditions, AERMOD predicted very large concentrations over the terrain close to the source, whereas in ADMS concentrations were more similar to the other cases (1 to 5). Differences did also show up in other ways. Plumes calculated by ADMS remained symmetrical, while the empirical correction of AERMOD would generate an asymmetric plume in an asymmetric terrain. One important terrain effect is the large scale modification of wind speed and direction over longer fetches of terrain. This can be important due to the essentially slender form of plume concentration contours at the ground, so that small changes in effective wind direction or plume rise can significantly modify local concentration patterns. The ADMS wind field model would generate such variations, AERMOD and ISC would not. Another critical feature of terrain calculations appears to be the choice of terrain and output grid scales, in both the ADMS and AERMOD/ISC types of terrain dispersion calculation. The limited investigation here has found that problems can be produced very easily with inadequately fine grid resolution for the terrain and the dispersion calculation. The most serious problem seems to be smoothing of terrain effects, to the extent of it appearing to have no effect at all. It has been noted earlier that none of the model manuals cover this, potentially quite serious, matter adequately.

One of the critical features of the AERMOD and ADMS models which became apparent during the study was the sensitivity of these models to the input meteorological data and the importance of the meteorological pre-processor to the calculated dispersion. The results of the calculations of the plume/boundary layer interaction in Section 4.3 give some idea of this sensitivity. A comparison can also be made between the calculations, in Figure 12 and 13, and with their equivalents in the basic dispersion calculations for the 150m buoyant stack discharge in Figure 8. The latter calculations were different only by way of the boundary layer depths (and therefore of H/L_{mo}), which are those given in Table 2 of Section 3.3. The ISC calculations showed no direct response to the boundary layer height, so serve as a reference between the plots. ADMS and AERMOD showed similar, but not identical, dispersion behaviour for the unstable boundary layers, but more marked variations in dispersion between the neutrally buoyant and stable boundary layers. This seemed especially so in view of the sensitivity of these models to the boundary layer's state and to the significantly different boundary layer states predicted by their meteorological pre-processors using the same input data. It was remarked in section 3.3 that the differences between the AERMOD and ADMS meteorological pre-processors for the few cases shown in Table 2 were disturbing. It appeared from this that differences in the respective meteorological pre-processor outputs might be as important as differences between the basic dispersion model themselves. The importance of the way in which meteorological data were assessed was also noted in the review of previous intercomparison studies (Hall et al (1999c)) which preceded this work.

Except in the single stable boundary case, the present study deliberately used the boundary layer inputs to the different models as supplied by their own meteorological pre-processors as these were provided as integrated packages which would process the raw meteorological data and pass it directly to the dispersion model. However, in view of the apparent sensitivity of the dispersion calculations to the input meteorology, this was investigated further. Figure 38 shows plots for identical individual hours of the outputs of the ADMS meteorological pre-processor against that of AERMET, the AERMOD meteorological pre-processor, for the Lyneham, 1995, data. There are plots of wind speed at 10m height, wind direction, boundary layer depth and $1/L_{mo}$, the inverse of the Monin-Obukhov length scale: 1:1 lines are marked on all the plots. There was no distinction in output wind speeds between the two pre-processors, nor between most of the wind direction estimates. There was, however, a band of data up the left hand side of this plot, for which AERMET provided wind directions and the ADMS pre-processor did not. These data are for zero wind speeds which are not used in calculations, but for which AERMET gives a variable wind direction and ADMS gives 0°. The pre-processors differed markedly over estimates of the boundary layer depth and the scatter in the data was large. AERMET mostly predicted much deeper boundary layers than the ADMS pre-processor, on average by about 50%. Also the ADMS pre-processor predicted a significant number of boundary layers of low depth, below about 200m, that AERMET did not, the band of data up the left side of this plot. The plot of $1/L_{mo}$ shows equally large variations, but of a more complex sort. Values close to the axis of this plot are of boundary layers close to neutral stability, values on the top right quadrant are of stable boundary layers, in the bottom left unstable. A high proportion of the data sits around the 1:1 line, though the scatter is large. There are also bands of data corresponding to (different) limit values set by the pre-processors. Thus AERMET limited L_{mo} mostly between about –1m and +10m, while the ADMS pre-processor applied only a positive (stable) lower boundary to L_{mo} of about +1m. The nature of the plot shows that the limit values were applied in quite different ways by the two models. It must also be noted that these limit values correspond to quite pronounced levels of boundary layer stability and instability that do not occur commonly; most of the data lie well inside these constraints.

It is possible to take the output of AERMET and use it directly in the ADMS model instead of in AERMOD. The opposite cannot be done because AERMOD requires data at two heights, which are calculated by AERMET, while ADMS only requires data at one height. Thus the single height data can be extracted from the AERMET output, but the additional height data cannot be readily created from the ADMS pre-processor output. Figures 39 and 40 show, respectively, concentration contours of annual dispersion calculations for two flat terrain cases, the 40m stack discharge without buoyancy and the 150m stack discharge with buoyancy. The annual mean and 99.9%ile are shown. The calculations show results for each model using its own meteorological pre-processor (these results are identical to those in Figures 21 and 22) and for ADMS using the output of the AERMET pre-processor. The maximum concentrations for the annual mean and three higher percentiles are shown in Table 14 for these and one other calculation. In this, the ADMS meteorological pre-processor data were extracted from the pre-processor and then re-input to their own model, as effectively were the AERMET output data, to check that this process did not affect the dispersion calculation.

The concentration contours for the 40m stack discharge, in Figure 39, showed no very marked changes in the concentration contour patterns from altering the meteorological input data to ADMS, the differences against AERMOD remaining similar. The concentration contours for the 150m stack discharge, in Figure 40, showed greater changes. Using the AERMET meteorological pre-processor input, the ADMS concentration contours showed much greater similarities to those of the AERMOD model.

It can be seen from the maximum concentration values in Table 14 that, for both stack discharge heights, some relatively small differences in the calculated concentrations (the largest is about 8%) resulted from entering the ADMS meteorological pre-processor data separately. For the 40m stack discharge height, entering the AERMET pre-processor output into ADMS resulted in changes in all the calculated dispersion parameters. The largest change, of about 9%, was in the 99.9%ile; the other parameters changed by a few percent. Compared with the differences against AERMOD run with its own meteorological data (about a factor of two in two cases), these changes were relatively small. For the 150m stack discharge height, the largest change in any parameter due to entering the ADMS meteorological pre-processor data separately was 4% (the 100%ile). Much greater changes in the calculated dispersion parameters resulted from using the AERMET pre-processor output in ADMS. All the calculated parameters increased markedly, by factors of 1.7-1.9. Three of the parameters became much closer to the values calculated by AERMOD, one (the 99.9%ile) became significantly different.

Table 14. Effect of meteorological pre-processor on annual calculations in flat terrain. (Maximum concentrations in mg m^{-3} for 1000g s^{-1} discharge)

Stack	Scenario	Mean (mg m^{-3})	100%ile (mg m^{-3})	99.9%ile (mg m^{-3})	98%ile (mg m^{-3})
40m Stack No Buoyancy	ADMS with ADMS Met Data Integrated Met input	0.73	120	68	12
	ADMS with ADMS Met Data Separate Input	0.77	120	69	11
	ADMS with AERMET Met Data Separate Input	0.79	110	69	11
	AERMOD with AERMET Met Data Separate Input	0.66	58	33	11
150m Stack with Buoyancy	ADMS with ADMS Met Data Integrated Met input	0.005	0.44	0.26	0.10
	ADMS with ADMS Met Data Separate Input	0.005	0.45	0.26	0.10
	ADMS with AERMET Met Data Separate Input	0.010	0.76	0.50	0.18
	AERMOD with AERMET Met Data Separate Input	0.008	0.70	0.29	0.15

5 ASPECTS OF MODEL USE

5.1 Availability and costs of models

This matter has been partly discussed in Section 2. The USEPA ISC and AERMOD models and the AERMET meteorological pre-processor for AERMOD are public domain models, for which the full technical specifications, algorithms and validation and verification data are available on the USEPA web site. One of the authors of this report downloaded the algorithms and technical documentation without difficulty. However, the ISC and AERMOD models in this form have fairly basic input and output procedures and the commercial versions of the models from Trinity Consultants and from Lakes provide more sophisticated input and output routines as well as advice on their use etc. The ADMS model is only available on a commercial basis from its single supplier, CERC Ltd. Technical information on ADMS is more limited (much of it has not been updated since the model's first appearance) and is often of insufficient detail to allow a full understanding of the model's behaviour. For general users there is no access to, or any detailed description of, the algorithms, and few example calculations are given.

If great sophistication in the input and output are not required, it would not be difficult, with the aid of spreadsheets and macros, for an individual to devise improved input and output procedures for the basic EPA models.

5.2 Computing equipment required

The minimum recommended for ADMS is a 266Mhz Pentium with 64Mbyte of RAM and 1Gbyte of hard disk.

AERMOD was designed to run on PCs with an 80386 or higher CPU, a minimum of 8Mbyte of RAM, a math co-processor and MS-DOS v3.2 or higher. ISC was designed to run on a machine with a minimum of 640kByte of RAM, MS-DOS v3.2 or higher. A math co-processor is recommended but not essential and extended memory versions are available for running on PCs with an 80386 or higher CPU. There is no recommended size of hard drive required for AERMOD or ISC, the amount of storage depending on the particular application. Both Trinity Consultants and Lakes software are 32 bit codes, requiring Windows 95, 98 or NT operating systems. The Trinity Consultants version requires a Pentium processor, a minimum of 32MByte of RAM and 100Mbyte of free disk space.

The present (approximate) costs of commercial model software (in £UK) are:

USEPA download	AERMOD		Free
USEPA download	ISC		Free
Trinity Consultants	'AERMOD Suite'	1 CPU Licence (indefinite)	£2400
		Annual maintenance and upgrades	£600
	'ISC Suite'	1 CPU Licence (indefinite)	£2400
		Annual maintenance and upgrades	£600
Lakes Environmental*	'ISC-AERMOD VIEW'**	1 CPU Licence (indefinite)	£1100
		Annual maintenance and upgrades	£330
CERC	UKADMS	Indefinite licence***	£5000
CERC	UKADMS	Annual licence****	£1600

* Now available from the UK Meteorological Office
** Lakes version includes AERMOD and ISC, together with the PRIME building downwash software.
*** Includes one years' helpdesk and upgrades.
**** Includes helpdesk and upgrades.

In practice it is advantageous to use higher specification computers, especially for the ADMS model. For annual statistical calculations, the most common regulatory use, all the models require reasonably up-to-date computers. All the models use all the available CPU when running, so that model run times are directly proportional to CPU speed. In addition the models use significant amounts of RAM, especially when calculating statistical parameters at the end of the run. On an annual calculation AERMOD and ISC will use nearly 100Mbytes of RAM and ADMS nearly 200Mbytes. If these amounts of free RAM are not available, disk swapping will result and the later stages of the calculation will be considerably slowed.

Some typical run times on a 500MHz computer with SCSI interfacing, ultra-fast hard disk and adequate free RAM, running on Windows NT, for a single stack annual calculation for a 31 x 31 grid of receptors (including calculation of percentiles) are,

	in flat terrain	with terrain model
AERMOD	About 2.5 minutes	About 2.5 minutes
ADMS	About 45 minutes	About 6.5 hours
ISC	About 1.75 minutes	About 1.75 minutes

These run-times are, of course, almost directly proportional to the number of sources and the number of receptors used. Additional RAM is also required for additional stacks, for example ADMS requires about 220Mbytes of RAM with two sources.

The heavy use of CPU and RAM by these models can make additional multi-tasking within the Windows environment difficult. Both the models themselves and other operating software will slow significantly. This is especially so of ADMS, which makes the heaviest computing demands. Even with Windows NT (a relatively stable operating system) it is possible to crash the computer if too many other applications are opened with ADMS.

5.3 Compatibility with meteorological and ordnance survey data

The models are mainly designed to operate with annual calculations and output statistics, which is the most common regulatory requirement. Meteorological data specially prepared for input to the three models on this basis are available from the UK Meteorological Office, from Trinity Consultants and from other sources. The input files are directly accepted by the models, but not directly interchangeable between them. Meteorological data from different sources are not invariably identical and may affect the details of some calculations. Hall and Spanton(1999a) have discussed this in greater detail.

Similarly, input of map and terrain data is possible in a variety of formats, including GIS. Ordnance Survey data are directly useable by ADMS and by Trinity Consultants version of AERMOD. Lakes AERMOD will currently take only NTF data but is being modified to accept GIS data.

5.4 Data input and output

All the commercial models have highly organised data input and output routines based on the Windows style of data handling. Interestingly, however, there remains a hard core of ISC and AERMOD users who prefer to use the basic USEPA input file directly and both Trinity Consultants and Lakes Environmental retain this option. All the models will accept prepared meteorological input data files without difficulty. Source input data files are also generally highly organised. It is possible (with Trinity Consultants AERMOD especially) to set up quite complex dispersion scenarios with multiple stacks, multiple buildings and fixed sampling receptors. The realism with which these inputs are handled in the dispersion model is another matter.

The models all allow different types of sources; AERMOD and ISC permit an unlimited number of sources of the following types:

point,
volume,
flare,
line,
area (square, rectangle, circle or polygon).

All the models allow time-variable pollutant discharges in some form.

In ADMS, input is restricted to 50 sources, of which no more than 5 may be area or volume sources and no more than one a line source. There is also a 'jet' source type.

AERMOD and ISC allow an unlimited size of receptor grid, whereas in ADMS there is a restriction to a maximum grid size of 32 x 32 receptors.

All the models provide output in a number of standard forms. Specific statistical data required for regulatory assessment can be requested and data can also be transferred to contour plotting software. All the models used the SURFER contouring software, which will provide contoured output in most desired formats. All the contour plots in this report were prepared in this way. The graphics options within ADMS were found to be useful for viewing graphs of centre-line concentrations and dispersion parameters. Neither AERMOD nor ISC provide this option. Terrain or map data in standard formats supplied by the Ordnance Survey or other sources can also be input readily to the models and can be output in combination with dispersion data. In ADMS the terrain contours were not generated automatically. It is also possible to set up terrain files from scratch, which was needed for the present study. In all three models this requires the writing of some code to create the terrain files in the correct format. For AERMOD there was also a need to generate additional code to create the receptor height scales. This could only be achieved after consulting the USEPA technical documentation.

Though their input and output procedures differed somewhat, overall all the models allowed conventional regulatory dispersion calculations to be carried out fairly quickly and effectively. Trinity Consultants package was probably the most versatile. For the type of modelling in the present report there was a slight preference for the ADMS input and output file structure. One advantage was that the output of new calculations was automatically sent to new storage files, rather than overwriting previous files if they were not re-labelled. However, none of the models had entirely foolproof input and output; file structures were sometimes ambiguous or difficult to follow. There was also a variety of software glitches and data interfacing problems (probably more with ADMS than with the other models), though these mostly classed as operational irritations rather than major faults. However, in a software application with a limited circulation (there are approximately 100 users of ADMS and fewer than 1000 of AERMOD and ISC) perfection cannot be expected. It would, however, be very helpful if known faults and problems were reported promptly to all users, especially if they affect the numerical output of dispersion calculations.

For more specialised applications or research studies which departed from conventional regulatory calculations, the models were of more variable utility. In this type of work it may be necessary to investigate specific aspects of annual calculations or to set up calculations for a particular single weather condition, as has been done in many cases in the present report. For example, there may be a desire to investigate dispersion patterns when there is precipitation or other particular weather conditions, at particular times of day or to investigate dispersion behaviour at a number of specific sites over a year. For this type of work it is necessary to access the meteorological input files, the meteorological pre-processor output files and the dispersion calculation grid output files on an individual hourly basis. It is then possible to set up sets of calculation files of a specific sort and to access them individually, or to interrogate yearly dispersion data for any desired criteria of time, meteorological condition or site. The ISC and AERMOD models provided this type of access as the outputs of the meteorological pre-processor, dispersion calculation and data analysis and plotting files were completely accessible. However, if these options are used, the output files, especially for an annual calculation, are large, of order 100Mbytes, and the format does not allow easy access to the data. ADMS was originally provided as a completely integrated package for which only statistically analysed output (over the calculation grid) was available. Access to the meteorological pre-processor output has been provided relatively recently, but in its standard form the ADMS model allows no access to the hourly dispersion calculation grid. This output file is also large (ca 100MBytes) and is normally lost on completion of a set of calculations. Thus single condition calculations can only be run singly and more specialised investigations are impracticable. It is possible to overcome these restrictions within limits by truncating the meteorological input file to required input cases, but this does not allow their individual examination.

It would be advantageous in many respects if model inputs and outputs, at whatever calculation stage, could be directly transportable to and from standard spreadsheets. It is often easier to handle input and output data in this way for various purposes, but such transfers are not always possible or easy. The models are more aligned to direct manual input of data or the use of specific formats (such as those for meteorological data) which are not always very convenient.

5.5 Range of applications

All the models dealt in some fashion with the basic dispersion behaviour investigated in this report. The level of complexity with which this was done varied considerably. Overall the older, ISC, model used the simplest approach to dispersion calculation and the ADMS model by far the most complex. This is reflected in the operating run times of the different models. Besides the dispersion parameters investigated here, the models deal with a number of other applications. ADMS and ISC will carry out deposition and washout calculations but at present this option is not available in AERMOD. ADMS requires a deposition velocity and a washout coefficient for each pollutant being modelled. The washout coefficient, Λ, can be specified as a constant value, independent of the precipitation rate. In this case wet deposition is calculated even when the precipitation rate is zero or if no precipitation is specified. Alternatively the washout coefficient can be calculated using,

$$\Lambda = Ar^B,$$

where r is the precipitation rate.
Constants A and B are dependent on precipitation rate and can be specified. Default values of $A = 10^{-4}$ and $B = 0.64$ are supplied.

In ISC, to calculate deposition, particle information including settling velocity and deposition velocity (for dry deposition) and scavenging coefficients (for wet deposition) and specially processed meteorological data are required. None of the washout models is entirely satisfactory for the short ranges at which the models normally operate.

All the models can provide concentrations averaged over different time periods. In AERMOD and ISC a wide range of periods from 1 hour up to monthly and longer period averages can be obtained. ADMS can calculate hourly and period averages as well as shorter-term values. ADMS also has a fluctuations module for simulating the variation in concentration caused by short time-scale turbulence in the atmosphere. This produces significantly different results from more conventional procedures. There have been some questions over its accuracy and it has yet to be fully accepted for regulatory work in the UK.

Within ADMS there are also facilities for modelling coastal effects, plume visibility, chemistry and radioactive emissions. These options all require extra input, of either meteorological parameters and/or background values of specific pollutants. Some cause difficulty in practical application

5.6 Response of suppliers

As noted earlier, none of the models considered here is perfect or the software glitch free. Also the use of complex models often raises problems that are not always readily answered in manuals, so that a technical advisory service can be very useful.

The basic EPA models provide fully detailed descriptions of the basic models; the algorithms are accessible, but otherwise there is no formal advisory service. Many of the EPA staff concerned with modelling and other involved parties (such as the members of the AERMIC committee) will provide considerate answers to intelligent questions if asked, but are under no obligation to do so.

Trinity Consultants and Lakes Environmental provide advice on their own versions of the EPA models for users on maintenance. Our experience of Lakes service is limited, but it has been prompt and intelligent. Trinity Consultants service is better known to us and is prompt and efficient, intelligent responses usually being received within 24 hours.

CERC also provide an advisory service for users on maintenance, of which we also have experience. Its response is more variable and queries sometimes go unanswered. During the course of the present study a number of queries arose over the working of the ADMS terrain model and these were formally posed to CERC. A response was received after four months, too late to be incorporated into this report.

6 DISCUSSION

The present study has considered the behaviour of the three models in nearly all the basic aspects of regulatory dispersion. Most of the aspects not considered here are either processes carried out subsequently with the calculated dispersion field, for example plume chemistry, deposition and washout, or are secondary interactions between different basic plume characteristics, such as the interaction between plume rise and buildings or terrain. Other matters such as shorter term concentration fluctuations and their effects on plume averaging times are complex matters in their own right beyond consideration here. Detailed discussion of the separate parts of the study have been placed in the appropriate sections of the report. This final discussion considers a number of overriding matters, including the general approach in regulatory applications and the philosophy required for model intercomparison studies.

The main purpose of the present study has not been to determine whether one model is 'right' or 'wrong', but to investigate the differences that may result between regulatory calculations using the different models and to determine whether they were of significant concern to regulatory activities. The absolute validity, or 'errors' in models can only effectively be found by comparison with physical observations of dispersion. Obvious errors or faults in the models are clearly relevant to the intercomparison process, but it was not presumed that a difference between models necessarily constituted an error. In general the present study has detected no 'errors' per se and the main problems have revolved around differences in the way models treat specific dispersion problems or meteorological data.

It has to be appreciated that the use of models for regulatory purposes imposes different requirements to what might be called 'research' investigations. In the latter, variations between models are not considered surprising and can be tolerated as part of a variety of scientific uncertainties. In regulatory applications, a model is used to assess a process against set guidelines (which are sometimes legal requirements) for pollution exposure. The exceedence or otherwise of these levels may affect the decision on whether the plant is permitted to operate or whether there should be significant expenditure on abatement equipment, process modifications or increased discharge stack heights. Differences of as little as 10% in a calculated concentration may alter the balance of major strategic decisions and expenditure.

In these circumstances models become regulatory tools, differences between models or between versions of models become more critical and it is important to know what these might be and how they might arise. This also applies to the ways in which models are used. It will be appreciated from the present study that in practice dispersion modelling is far from being a scientifically standardised activity with commonly agreed methods. In applications for regulatory authorisation, it must also be expected that a dispersion study may be carried out in a way which favours the desired result. This is not improper per se (as would be falsifying emission data, for example) and is akin to the process of tax avoidance (rather than evasion), but it is important for the regulatory assessor to appreciate those features of a study that may alter its outcome in this way. The choice of model, where there is one, may be one of those features. The latter problem can be avoided by specifying the use of a particular model, as for example have the USEPA with ISC, which is expected to be replaced by AERMOD in due course. However, this approach is unusual in the UK, where the regulatory authorities have avoided it for a number of good reasons. Amongst these, it allows applications for authorisation to consider more carefully the basis of their calculations and to ensure that new scientific developments and knowledge are rapidly assimilated into regulatory practice.

In the UK, information to guide the regulatory authorities in these matters has so far, been limited, patchy and inconsistent, as the review preceding this study (Hall et al(1999c)) has shown. Over about the last five or six years a single model, ADMS, has been used in the UK for the bulk of regulatory air dispersion calculations. This has to some extent avoided the need for guidance on the differences between models, though not on the subtleties of its use. However, during this period this model has passed through about seven or eight versions or revisions and there has been limited guidance on what differences in dispersion calculations may have arisen between these. The USEPA does not permit such a casual approach and any changes to a regulatory model have to be fully assessed and the results published. The need for the present study has arisen from this regulatory problem and from the stimulus of the introduction of the AERMOD model. It has had two main aims. The first has been to lay out a standard test protocol which can be used in the longer term for examining the differences between dispersion models and their successive versions from a regulatory viewpoint. The second has been to carry out the first such study using this protocol.

After its first use, we feel that the test protocol that we have laid out has generally served its required purpose and represents a firm basis for a comparative procedure in the longer term. Though the annual calculations have been the most directly relevant in regulatory applications, the single condition calculations have been equally important in revealing specific differences between the models in a way which is well ordered and allows the physical reasons for the differences to be more readily identified.

The intercomparison study itself has shown differences between the models that are large by regulatory standards and also in comparison with the differences commonly encountered when considering different regulatory options. They cannot therefore be ignored. On a simple bulk count of the model concentration ratios in the bar charts and Tables shown here, about 28% of the ADMS/AERMOD ratios exceeded a factor of two, of which 15% were high (>2) and 13% low (<0.5). Of the ISC/AERMOD ratios 38% exceeded a factor of two, of which 35% were high (>2) and 3% low(<0.5). The majority of the differences exceeded 20%. A simple description of these data would be that, overall, ADMS produced concentrations that were a little higher than AERMOD and that ISC produced concentrations that are more generally higher than AERMOD and, by inference, higher than ADMS. It must be appreciated, however, that all the pollutant must go somewhere, so that a variation in concentration at the ground must be accompanied by some other change, in plume rise or lateral spread for example. However, in searching for consistent differences in behaviour between the three models, one of the conclusions of the study is that there do not seem to be many. Even the quite specific individual aspects of dispersion examined here, which have been discussed in Section 4.8, have exhibited quite variable relationships between the models. It is not, therefore practicable to offer reliable blanket guidance on the differences between them. Guidance from the intercomparison is therefore best achieved by examining those aspects closest to the specific problem in hand.

In view of the quite different character of the AERMOD and ADMS models against the, older, ISC model and their use of more recent research results, it would not be surprising if relatively large differences in calculations existed between these two and ISC. However, the relatively large differences at times between ADMS and AERMOD are more surprising. They both incorporate the effects of boundary layer height and Monin-Obukhov length scale on dispersion, are based on essentially the same research database and calibrated against largely the same field measurements. Their major differences lie in their approach to building effects and terrain, though in the former case the far-field predictions are not so different. It appears from this study that dispersion rates in both models are quite sensitive to changes in the boundary layer height and Monin-Obukhov length scale, but not in identical ways. Hanna et al's(1999) recent intercomparison of the three models with some field data sets also found significant variations between the two models' response to different (highly variable) field data sets, though overall ADMS appeared to fit the field data somewhat better than AERMOD; both were significantly better than ISC.

There are two possibilities with regard to this apparent sensitivity of AERMOD and ADMS to the meteorological inputs. The first is that it is physically real. If so this carries implications for the ultimate reliability of dispersion calculations and the resultant need for calculations over sufficient time to provide reasonably stable average data and some indication of the variability. Annual calculations over several years (perhaps five) would be required to obtain both reasonably stable average values and information on year-to-year variability. The second is either that the models are excessively sensitive to the main governing parameters of the dispersion, or that they are suffering from excessive variability in handling the effects of a larger number of governing parameters than are required in the older Pasquill/Gifford (ISC) type of model. A colleague has aptly described this latter problem as 'noisy sophistication'.

A major problem with the advanced models, especially in view of their apparent sensitivity to the meteorological inputs, is the variability in their own calculated input meteorological data. The differences between the ADMS and AERMOD (AERMET) meteorological pre-processors and their effects on dispersion calculations were quite marked and may well be one of the major causes of differences between the two models. As was remarked in Section 3.3 and considered in more detail in Section 4.8, the large differences in the calculated boundary layer conditions of ADMS and AERMOD from identical basic inputs are quite disturbing and merit detailed investigation in their own right. If this is the level of uncertainty associated with the analysis of raw meteorological data, then it would appear to be inadequate to ensure reliable use of advanced dispersion models.

In view of this apparent sensitivity to meteorological inputs, the further question of the adequacy of the raw meteorological data becomes more important. In the UK there are approximately 80-85 sites providing data considered ‘adequate’ for the more sophisticated needs of advanced dispersion models. None is designed specifically for this purpose (many are on RAF sites) and overall the number seems likely to reduce rather than increase. Though apparently numerous, when distributed over the UK, the network appears relatively sparse and some sensitive areas for pollution studies are poorly served meteorologically. In many cases, therefore, dispersion studies must be made using data remote from the site of interest and whose local applicability is uncertain. Unless this situation is likely to improve, there would seem to be practical limits to the degree of sophistication that it is worth building into dispersion models and we may well be approaching those limits in some applications.

At present it would appear that the science of the advanced dispersion models and of processing the required meteorological data is still in a state of flux and that it may be some time before scientific opinion converges to a degree of agreement on a par with that of the Pasquill/Gifford models (such as ISC). This does not diminish their usefulness, or the need to use them. They allow far more versatility in calculations than previously and undoubtedly represent many forms of atmospheric behaviour more realistically. However, they do appear to need using with caution and some understanding of the uncertainties in their behaviour. The present study has attempted to supply this. One consequence of the present state of affairs is the clear need for studies of this sort to be continued over time and to retain as much as possible a continuity in their approach if much of their value is to be retained. It has also become clear to the authors that the disinterested nature of such studies should be paramount. The review preceding this work found few such disinterested studies.

It also seems clear that the open exchange of scientific information and critical scientific appraisal of advanced models is essential if the convergence of scientific opinion as to their most effective form is to occur in any reasonable time. This has not been a problem with the AERMOD and ISC models, whose public domain nature has provided full details of the models, their algorithms, critical appraisals and field calibration studies. It has also been the subject of much open discussion and comment. The main commercial constraints have been with the input and output algorithms provided by Trinity Consultants, Lakes Environmental and others. The value of these components has been concerned with user convenience and has not directly affected scientific openness. However, it has proved a more serious obstacle with the ADMS model. Despite having been developed largely from government funds or with input from government funded organisations, it has been treated as a proprietary model. It has been difficult to discern the details of its operation or its sensitivity to input information and it has been the subject of limited published constructive criticism or disinterested independent assessment. The technical background documentation is patchy and rarely indicates clearly the processes occurring in the model. Most of the technical documentation appears to have been unaltered since the first appearance of the model, despite its many modifications, and there are few examples of realistic calculations showing the behaviour of the model in different circumstances. We believe that this approach is unhealthy, stifles the effective development of advanced dispersion models and has specifically hindered the effective development of the

ADMS model. Furthermore, we see no need for it, even for commercial reasons. As with the commercial suppliers of the AERMOD model, the value to the user is in effective guaranteed software and nothing is lost commercially (and everything gained scientifically and practically) by a more open approach.

There seems to be a very good case for considering the discrete components of these models, the meteorological pre-processor, the dispersion calculation itself and the subsequent data handling software as separate entities and to use them independently as desired in complete calculations. This would both concentrate attention on the critical aspects of these essentially separate items and encourage their individual development, for which there appears to be a scientific need. This approach is well within practicable bounds.

We conclude by repeating the remarks made in the review preceding this study concerning the UK Royal Meteorological Society's Policy Statement on Atmospheric Dispersion Modelling (R Met Soc(1995)), which discussed the requirements of effective use and development of dispersion models, including the need for 'Quality Assurance' and 'Auditability' of models and data derived from their use. It also drew attention to the responsibilities that fall on the various interested parties (including the regulatory authorities and the providers and users of modelling services) to actively promote best practice. There is still much scope for the adoption of the guidelines and principles proposed in the policy statement, which would greatly encourage more rapid development of advanced dispersion models and a better understanding of their use.

7 CONCLUSIONS

1. The study has developed a protocol for comparing dispersion models in order to distinguish the critical differences between them in regulatory applications. This has involved setting standard test cases for examining both the specific individual characteristics of the models, by way of single condition calculations, and for the results of typical regulatory calculations, by way of annual calculations. The test protocol has been applied to three dispersion models used in regulatory practice in the UK, the older, Pasquill/Gifford ISC model and the 'advanced' AERMOD and ADMS models, which base dispersion rates on the boundary layer depth and the Monin-Obukhov length scale.
2. The test protocol has covered basic dispersion from two discharge stack heights (40m and 150m) with and without the addition of buoyant plume rise, buoyant plume interaction with the top of the boundary layer, the effects of surface roughness, building entrainment and a range of terrain forms based on the Porton Down test range.
3. The test protocol has been found to be generally effective in operation and has largely provided the required information. It is intended to serve as a basis for continued comparative model calculations of this sort over time, so that the relative behaviour of new models or new versions of models can be assessed on an historical basis.
4. Overall, the models have shown, by regulatory standards, significant differences and high levels of variability against one another in the different test cases, so that it is difficult to discern any consistent relationships between them. Overall, they agreed most closely in neutrally stable boundary layers with the lower source height, 40m, used here. On a simple bulk count of the model maximum concentration ratios in the bar charts and Tables shown here, about 28% of the ADMS/AERMOD ratios exceeded a factor of two, of which 15% were high (>2) and 13% low (<0.5). Of the ISC/AERMOD ratios 38% exceeded a factor of two, of which 35% were high (>2) and 3% low (<0.5). The majority of the differences exceeded 20%. However, the highly variable nature of the differences between the models

makes such statistics of limited value. The greatest similarities tended to occur in neutral stability boundary layers near the ground, and diverged with increasing source height or non-neutral stability. However, this behaviour was not perfectly consistent.

5. Dispersion rates in the advanced models have generally proved quite sensitive to values of the boundary layer height and the Monin-Obukhov length scale.
6. It has been found that the meteorological pre-processors are a critical feature of the advanced models' behaviour and that those for AERMOD (AERMET) and ADMS produce significantly different estimates of boundary layer height and the Monin-Obukhov length scale, the critical parameters for advanced dispersion model calculations. These variations were sufficient to alter significantly the output of annual dispersion calculations required for regulatory purposes.
7. It appears that at present the 'advanced' dispersion models (AERMOD and ADMS) are still in a state of scientific development in comparison with the earlier Pasquill/Gifford models. This does not diminish their predictive usefulness. They offer improved versatility and performance in many aspects of dispersion modelling. However, some caution and understanding is needed in their use. The further development of these dispersion models, and of their meteorological pre-processors, should be encouraged by an open attitude to their contents and working. For the ADMS model, this openness is hindered at present by the commercial confidentiality surrounding its detailed operation.

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APPENDIX 1

MODEL PROCEDURES FOR DISPERSION OVER TERRAIN – TECHNICAL DESCRIPTION AND DISCUSSION

Introduction

The ADMS, AERMOD and ISC models all approach the effect of terrain on dispersion calculations in different ways. In this Appendix we give a brief overview of method employed by each model and discuss some of the practical implications for the model user.

ADMS

Concentration equation

ADMS also employs two forms of the concentration equation, depending on the stability conditions. Stability is defined according to the h/L_{mo} classification. Thus for convective conditions ($h/L_{mo}<-0.3$) concentration is calculated from

$$C\{x_r, y_r, z_r\} = \frac{Q}{2\pi U(z_\eta)\sigma_y} \cdot \exp\left(\frac{-y_r^2}{2\sigma_y^2}\right) \cdot \left(\begin{array}{l} a_+ H\{z_r - z_\eta - \hat{w}t\} \dfrac{\exp\left(\frac{-(z_r - z_\eta)^2}{2\sigma_{z_+}^2}\right)}{\sigma_{z_+}} + \\ a_-[1 - H\{z_r - z_\eta - \hat{w}t\}] \dfrac{\exp\left(\frac{-(z_r - z_\eta)^2}{2\sigma_{z_-}^2}\right)}{\sigma_{z_-}} \end{array} \right) \quad \text{(a1)}$$

where H is a step function. For neutral-stable conditions ($h/L_{mo}>1$)

$$C\{x_r, y_r, z_r\} = \frac{Q}{2\pi U(z_\eta)\sigma_y\sigma_z} \cdot \exp\left(\frac{-y_r^2}{2\sigma_y^2}\right) \cdot \left(\exp\left(\frac{-(z_r - z_\eta)^2}{2\sigma_z^2}\right) + \exp\left(\frac{-(z_r + z_\eta)^2}{2\sigma_z^2}\right) \right) \quad \text{(a2)}$$

is used. For convective-neutral conditions ($-0.3<h/L_{mo}<1$) a weighted combination of equations a1 and a2 is used.

These equations differ from their equivalents without terrain in a number of ways. The deflected mean streamline height (z_η) is used in place of the source height (z_s) in the vertical term for the wind speed (U) and the dispersion coefficients are calculated from specific terrain related formulae. ADMS also allows for reflection at local ground level at the receptor in the image terms (i.e. z_η is replaced by $2h_t\{x_r, y_r\} - z_\eta$) as well as at the mixing height.

The main difference between ADMS and AERMOD, with regard to terrain, is that ADMS calculates a perturbed mean and turbulent velocity field over the terrain using the linear wind flow model FLOWSTAR. The perturbed wind field consists of the background wind (over no terrain) and an additional component due to the presence of the terrain. The new wind field is then used to determine the deflection of the mean streamline (wind speed constant) through the source using the non-linear equation,

$$(U + \Delta u)\frac{d\eta}{dx} = w_\eta(x, y, Z_s + \eta\ ) . \qquad \text{(a3)}$$

In the above $Z_s = z + h_t(x, y)$. The deflected streamline height ($z_\eta = z + \eta$) and the modified mean wind speed ($U + \Delta u(z_\eta)$) are input in equations a1 or a2. The turbulent velocity field is used to prescribe the dispersion coefficients. The perturbed wind field and the mean streamline depend on terrain gradients rather than the actual terrain height.

The equation for concentration in the convective boundary layer in ADMS (Equation a1), obtains the concentration over terrain by replacing the source height (z_s) by the deflected mean streamline height (z_η), which itself is obtained from equation a3. The dispersion parameters are also replaced by terrain modified values. Hence the relative size of z_s and z_η compared with $\hat{w}t$ mainly determines the difference between the concentration predictions with and without terrain. Since, by definition, t = x/u, this is essentially the same as the expression used in AERMOD (although $\overline{w}$ and $\hat{w}$ may be different) and the same arguments apply. Thus for terrain cases 1 and 6 used here the mean streamline deflection was significant compared with the plume rise close to the source.

The terrain calculation has to be repeated for each hour's meteorological data and the wind field has to be calculated at a number of heights in order to obtain w_η. It is not clear if there is any calculation of the lateral deflection of the mean streamline in which case the mean horizontal wind direction remains unchanged from its initial (unperturbed) value. However, previous work with FLOWSTAR over similar terrain and stability conditions to the current study indicate that the mean flow would not be deflected by more than a few degrees from the background direction. This would not have a significant effect on the predicted concentrations at standard output grid spacings. All the components of the concentration equation are symmetrical about this streamline, which follows the initial (unperturbed) mean wind direction. Hence the model output will be symmetric about the plume centreline in the x-y plane.

FLOWSTAR

FLOWSTAR is a linear wind flow model which can be purchased as a stand-alone model from CERC. It is incorporated in ADMS but the wind field is not output. More details can be found in Carruthers et al 1988.

Linear wind flow models use a Fourier transform of simplified flow equations, subject to appropriate boundary conditions, to obtain an approximate analytical solution for the flow field over terrain. The linear solutions consist of a spatial coefficient which can then be multiplied by a height term and added to the background wind to give the modified wind field. In FLOWSTAR stability effects are introduced via the Brunt-Vaisala buoyancy frequency, N, for $h/L_{mo}>0$.

The use of linear models is constrained by the assumptions made in the simplification of the governing equations and by the practical limitations of Fourier transform techniques.

Typically, fast Fourier transform techniques require a $2^n x 2^n$ (e.g. 32x32, 64x64 etc) grid with data at regular spacing. In wind flow models it is the terrain elevations that are transformed. Hence the size of the model domain must be such that the terrain detail can be resolved over this number of points. As with AERMOD, the extent to which the plume will respond to local changes in terrain or larger scale features, and therefore the effect of terrain resolution on the modelled concentration, will depend on the source type and meteorology.

The Fourier transform is also a periodic function. It therefore assumes that the terrain repeats its shape upwind and downwind of the model domain. The model domain should thus incorporate all the terrain features in the area of interest. This problem is often overcome by extending the model domain and curve fitting between the edges of the model domain over this "buffer" zone. Documentation for the FLOWSTAR User Guide indicates that it buffers the domain over 10% of the original. In ADMS the output grid must also be 100m from the terrain boundary. It also appears from the documentation that FLOWSTAR subtracts out the mean slope between the edges of the model domain. Again, the model domain should be chosen carefully so that this process does not remove important terrain information.

Output domain

The predicted concentrations are output on a separate grid to the terrain grid. This grid is also user specified up to a 32x32 limit (and 100m from the terrain boundary). FLOWSTAR rotates the terrain grid to match the mean wind direction. Thus when a full year's data are run this means that it must be possible to rotate the output grid within the terrain grid over a full circle of wind directions. The output grid spacing should be sufficient to resolve the effect on the concentration distribution due to the terrain. As a 32x32 grid is recommended by CERC as standard for terrain, using an output grid close to the maximum size will give comparable output and terrain resolution.

AERMOD
Concentration Equation

AERMOD initially determines the form of the equation used in the concentration calculation from the stability conditions. Hence, regardless of the composition of the model domain, if $L_{mo} < 0$ the equation for a given receptor point (x,y,z) has the general form in unstable boundary layers of,

$$C\{x_r, y_r, z_r\} = \frac{Q}{2\pi \underline{u} \sigma_y} \cdot \exp\left(\frac{-y_r^2}{2\sigma_y^2}\right) \cdot \sum_{j=1}^{2} \frac{\lambda_j}{\sigma_{zj}} \left[\exp\left(\frac{(z_r - z_e)^2}{2\sigma_{zj}^2}\right) + \exp\left(\frac{(z_r + z_e)^2}{2\sigma_{zj}^2}\right) \right] \qquad \text{(e1)}$$

where z_e is the effective source height and λ_j weights the up- and downdraft contributions.

In stable boundary layers, if $L_{mo} > 0$, the solution has the form,

$$C\{x_r, y_r, z_r\} = \frac{Q}{\sqrt{2\pi} \underline{u} \sigma_z} \cdot F_y \cdot \left[\exp\left(\frac{(z_r - z_e)^2}{2\sigma_z^2}\right) + \exp\left(\frac{(z_r + z_e)^2}{2\sigma_z^2}\right) \right] \qquad \text{(e2)}$$

where F_y is a lateral distribution function with meander.

The boundary layer parameters used in these equations are stability dependent and are not modified by the presence of terrain. Wind speed is averaged over the depth of the plume. The total concentration will also include additional modified terms due to image sources, indirect sources etc, which try to model particular stability related effects. The reader is referred to the technical documentation on AERMOD available from the US EPA website for a full description (Paine et al 1998).

When the model domain contains terrain then AERMOD represents each of the concentration terms used in the calculation for a plume over terrain as a weighted combination of the concentration from a horizontal plume state (C_h) and a terrain following plume state (C_t). The horizontal plume state represents the contribution from the plume impacting on the terrain and treats the terrain as a flagpole receptor. In the terrain following part the plume is carried over the terrain and continues to disperse as though the terrain was locally flat.

$$C\{x_r, y_r, z_r\} = f \cdot C_h\{x_r, y_r, z_r\} + (1 - f) \cdot C_t\{x_r, y_r, z_p\} \qquad \text{(e3)}$$

The formulae used to calculate C_h and C_t will both take the form of Equation e1 or e2, depending on the stability, and are essentially the same but with z_r, the receptor height above the stack base, in C_h replaced by z_p, the receptor height above the terrain, in C_t. So, for the case of ground level concentrations, z_r is the local terrain height (h_t) and z_p is zero. In addition, the effective parameters for the plume (namely $\underline{u}$, Φ_y and Φ_z), which appear in the concentration formulae, will also be calculated in a slightly different manner for C_h and C_t as they depend on the plume centroid height and the receptor height above the stack base (i.e. the plume half width). However, their values are not otherwise terrain related. The resulting plume can be asymmetric if the terrain is not symmetric about the centreline.

All receptor heights in the model are taken relative to the stack base elevation. So this height above a reference level (mean sea level or local zero terrain level) must be entered in the model. It appears from the documentation that the image sources in the concentration equations are not adjusted for the presence of the terrain. It is also assumed that the boundary layer height is not terrain following.

The weighting function, *f*, in Equation e3 has the form,

$$f = 0.5 \cdot (1 + \Phi_p), \qquad \text{(e4)}$$

where,

$$\Phi_p = \frac{\int_0^{H_c} C\{x_r, y_r, z_r\}dz}{\int_0^{\infty} C\{x_r, y_r, z_r\}dz} \qquad \text{(e5)}$$

and

$$0.5 \cdot u^2\{H_c\} = \int N^2 (h_c - z)dz, \qquad \text{(e6)}$$

where h_c is the receptor height scale for a given receptor (see below).

The weighting function is stability dependent and has a minimum value of 0.5, which is the fixed value in unstable conditions. Hence, even under convective conditions, some of the plume is assumed to impact on the terrain.

The variable Φ depends on the potential temperature gradient in the boundary layer and increases with increasing stability. It also depends on the dimensions of the surrounding terrain. This results in a greater proportion of the plume impacting on the terrain rather than rising over it, as conditions become more stable. Equation e6 embodies the concept of the critical dividing streamline height (H_c). There is insufficient energy in the flow to transport the proportion of the plume below H_c over the terrain feature.

Receptor height scale.

In AERMOD, concentration is calculated at a number of specified receptor points. H_c and hence f are also calculated at each of these points. The calculation requires that each receptor has an associated receptor height scale (h_c). This is the terrain height scale which will determine whether the oncoming flow can pass over or spread round the terrain feature. In AERMOD it is determined from

$$h_c\{x_r, y_r, z_r\} = \max(h_t\{x, y, z\}e^{-r/r0}) / e^{-r_{\max}/r_0}, \tag{e7}$$

where h_t is the elevation at a point on the terrain grid with distance r from the receptor of interest and r_{max} is the corresponding distance to the receptor from the terrain point with height h_c.

$$r_0 = 10 \cdot \Delta h_{\max} \tag{e8}$$

$\Delta h_{\max}$ is the maximum elevation difference in the terrain domain (multiplied by a factor of ten, chosen somewhat arbitrarily). The calculation is made with all terrain points for a given receptor and the maximum value taken. (In the equations for AERMAP, Equation e7 is multiplied by a function but this is then assumed to be unity and so is not included here.)

The formula for concentration in the convective boundary layer used in AERMOD is given in Equation e1. It can be seen from this that, if the height of the plume at a given distance downwind of the source (z_e) is sufficiently large compared with the height of the terrain, then h_e will dominate the vertical term in Equation e1. This applies to both the terrain following (z_p=0) and flat terrain (z_r=h_t) components of the plume (Equation e3). Hence the formula reverts to approximately the case without terrain (z_r=z_p=0). An equal weighting is given to both plume components under unstable conditions (f=0.5). It can be seen that the terrain has no influence on points in the model domain which are flat even if they are close to the hill.

Under unstable conditions, even without stack buoyancy there was some plume rise (Δh) in the discharge. In addition, convective up- and downdrafts modify the effective mean height of the plume, which is given by,

$$z_e = z_s + \Delta h + \frac{\overline{w_j} x}{\underline{u}};\ j = 1,2\,. \tag{e9}$$

So for the conditions used in the study, depending on the size of the up- and downdrafts (but assuming, for example, that $\overline{w} = 0.1\underline{u}$), then at 400m downwind the plume height was over twice the maximum terrain height. However, close to the source when the plume rise was small the terrain was flat and therefore did not affect the dispersion of the plume (except in case 6). Under stable conditions, maximum plume rise was comparable with the hill height for case 6 with consequent effects for the dispersion calculation close to the source.

It is clear that, for a plume upstream of an isolated terrain feature, h_c is a useful concept. Indeed the dividing streamline ideas have mainly been applied to such terrain under strongly stable conditions in the US (e.g. Cinder Cone Butte). However, for terrain which is less severe in slope but more complex in form, under weaker stability conditions the overall dimensions of the hill may not be the most critical factor in determining what happens to the plume.

There are a number of practical problems with applying the receptor height scales for regulatory purposes. These arise from the need to obtain statistics from a year's data. Over this period the mean hourly wind direction will vary considerably, but the receptor height scales remain fixed and the model does not discriminate between terrain upstream and downstream of the source. For example, consider two receptor points which are at the same height and distance from a source and with identical receptor height scales, but for given wind directions one is on the lee slope of a hill and one is on the upwind slope. AERMOD would predict identical concentrations at the two points if all other meteorological data were the same. Hence the plume is expected to impact on the hill or spread round it even if on its lee slope.

Under neutral and stable conditions the dominating contribution is from the horizontal plume component in which the terrain is treated as a flagpole receptor relative to the stack base. The way in which the image sources are calculated may have an effect on the concentration calculation close to the source in this situation where the receptor has a negative height relative to the stack base. An additional effect of the lack of directional discrimination in the receptor height scale method can be seen when it is applied over complex (non-isolated) terrain. If a source is located in a valley between two hills, then it is possible in principle (depending on the scales involved) that the larger of the hills will determine the concentration predicted on the smaller, whatever the wind direction.

Model Domain

For a given set of meteorological input conditions the equations used to calculate the concentration and associated boundary layer parameters are determined by the model. The user can influence the result of the modelling exercise through the choice of receptor locations. This is particularly important when the model domain contains terrain. The terrain heights used in the concentration calculations are those of the receptor locations. If the receptor grid is too sparse then terrain elevations and complexity may be lost which would affect the predicted plume behaviour. In AERMOD it is possible to use a number of receptor grids to look at particular regions of interest. This facility, together with the speed of the model, means that detailed grids can be used. However, when localised grids are used, terrain from a larger grid, which contains all the features expected to affect the local dispersion, should be used to determine the appropriate receptor height scales.

ISC

The same form of the concentration equation is used for all stability conditions in ISC but the dispersion parameters are stability dependent. Over level terrain this has the form,

$$C\{x_r, y_r, z_r\} = \frac{Q}{2\pi U(z_s)\sigma_y\sigma_z} \cdot \exp\left(\frac{-y_r^{\ 2}}{2\sigma_y^{\ 2}}\right) \cdot \left(\exp\left(\frac{-(z_r - z_e)^2}{2\sigma_z^{\ 2}}\right) + \exp\left(\frac{-(z_r + z_e)^2}{2\sigma_z^{\ 2}}\right)\right) \qquad \text{(i1)}$$

Over complex terrain a 22.5^{o} sector averaged version is used. This has no lateral component.

$$C\{x_r, y_r, z_r\} = \frac{Q \cdot CORR}{\sqrt{2\pi} U(z_s) R \Delta\varphi \sigma_z} \cdot \left(\exp\left(\frac{-(z_r - z_e)^2}{2\sigma_z^{\ 2}}\right) + \exp\left(\frac{-(z_r + z_e)^2}{2\sigma_z^{\ 2}}\right)\right) \qquad \text{(i2)}$$

R is the radial distance and $\Delta\varphi$ the sector angle. CORR is a stability related attenuation factor for terrain and σ_z takes the same values as in equation i1. In common with AERMOD and ADMS the ISC equations also have additional terms for reflection at the mixing height. More details can be found in the ISC technical documentation.

When modelling dispersion over terrain, each receptor point on the terrain is classified as 'simple', 'intermediate' or 'complex' and this determines the concentration equation used. In ISC, Briggs' plume rise formulae are used to calculate the effective height of the plume (z_e). When terrain is involved a new effective height is determined.

$$z_e' = z_e - (1 - F_t)h_t; \qquad F_t = \begin{cases} 0.5 \ \ for\ A - D \\ 0.0\ for\ E - F \end{cases} \qquad \text{(i3)}$$

When a point on the terrain grid is lower than the physical stack release height, it is classed as 'simple' and equation i1 is used with the effective plume height replacing the source height. An 'intermediate' terrain point is one which is greater than the stack release height but less than the effective plume height as defined in Equation i3. For this case, the concentration is calculated using both Equations i1 and i2 and the more conservative value is adopted. When the terrain height exceeds the effective plume height it is 'complex' and equation i2 is used to calculate the concentration. In all these methods the effect of the local terrain directly enters the calculation through z_e', while the receptor heights are above local terrain heights. The mixing layer height is also terrain following.

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APPENDIX 2

PLUME RISE AND INTERACTION WITH THE BOUNDARY LAYER'S CAPPING INVERSION

When a buoyant plume rises through a neutrally stable atmosphere its buoyant force remains constant, irrespective of its entrainment of the surrounding fluid. Such entrainment, of course, increases the plume's mass so it rises more slowly as it spreads; nevertheless, as long as the surrounding atmosphere is neutral, the plume retains positive buoyancy and should continue to rise. Various schemes have been proposed for defining a final rise and have been employed in the models under study.

A simple entrainment hypothesis suggests that bent-over plumes should be conical with radius $r=\beta z$, where z is the height of the plume centreline above the emission point and $\beta = 0.6$. In a neutral boundary layer capped with an inversion, the top of the plume thus meets the inversion when $(1+\beta)z = Z_i - h_s$, where Z_i is the height of the inversion and h_s is the stack height. For a thermal emission of q_T, the temperature excess in the plume relative to ambient at this point is given by,

$$\Delta T = \frac{q_T}{\rho c_p \, u \, \pi(\beta z)^2}$$

Thus, for q_T = 500 MW (a very large source) and a wind speed, u = 5 m s^{-1}, we should have:-

z/m	r/m	Z_i-h_s/m	ΔT/^{o}C
50	30	80	29.2
100	60	160	7.3
200	120	320	1.8
400	240	640	0.46

Such values may be compared with the temperature change of a few degrees Celsius through a typical capping inversion, or the typical potential temperature gradient in the overlying inversion of 0.5 ^{o}C/100m. It may be seen that the plume from a very large source might rise several hundred metres and still stand some possibility of escaping from the boundary layer. More typical industrial sources, with thermal emissions of a few tens of MW, will be trapped if Z_i-h_s is greater than 50 - 100 m.

Lidar observations (Bennett 1995) have supported the above view that the rise of a plume with $Q_T \approx 50$ MW, at least in UK conditions, tends to be terminated when it arrives at the top of the boundary layer. This model fitted the observations better than a model due to Briggs (1984) where the rise was terminated in convective conditions by the break-up of the plume. Neither model might in fact be appropriate for predicting maximum ground-level concentrations in convective conditions: an alternative 'touchdown' model considers the 'final' rise to be that at the downwind distance where elements of the plume first reach the ground (Briggs 1984).The ISC model compares a Briggs model of the final rise of the plume with the predicted boundary-layer depth. If the predicted rise is greater than Z_i-h_s, then the plume is deemed to escape and ground-level concentrations are zero. In the model calculations we made for the neutral case with Z_i = 200 m, we may estimate that for h_s = 150 m, q_T = 35 MW and u = 3.6 m s^{-1} then ΔT = 7.3 ^oC at the point where the plume reaches the top of the boundary layer. It is thus quite reasonable to assume that in this case the plume will mostly escape from the boundary layer; ISC does indeed predict this. ADMS and AERMOD with their more sophisticated schemes predict that something between 1/3 and 1/2 of the plume will remain trapped.

In the case of ADMS (Robins et al. 1999), the plume is modelled as a near-horizontal cylinder which rises until its net buoyancy falls to zero. The fraction remaining below the inversion height at this point is then considered to be trapped in the boundary layer, while the rest escapes. (Even if the plume escapes completely, it is not forgotten: sedimentation may return it to the boundary layer). This scheme is doubtless a simplification of reality but provides a plausible and seamless transition between complete escape and complete trapping.

The AERMOD scheme is more complex in as much as it divides the plume between that from the direct source, that from a virtual source reflected in the top of the boundary layer, and that from a virtual source within the capping inversion. After some delay, pollutant from these virtual sources is then fed back into the boundary layer. This scheme again provides a gradual transition between complete escape and complete trapping, but at the cost of introducing a great deal of unobservable complexity.

More generally, it should be noted that a detailed calculation of the extent to which the plume will escape from the boundary layer relies on parameters which are inaccessible or uncertain: the strength of the capping inversion, and the depth of the boundary layer. In the case given above, had Z_i been 300 m instead of 200 m, *ÄT* would have fallen to 0.8 ^oC and the plume would probably not have escaped. As may be seen from Table 2, it is not very easy to predict the boundary-layer depth to this degree of precision.

Overall, the more sophisticated approaches of ADMS or AERMOD are less likely to give a serious error than the complete penetration or entrapment approach of ISC. This is not to say that sophistication is justified in the face of uncertain input data. Rather that, in simulating partial trapping and a slow release from the top of the boundary layer, both ADMS and AERMOD have, in their different ways, provided a more realistic proportionate approach to plume entrapment.

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