# A Review of Dispersion Model Inter-comparison Studies Using ISC, R91, AERMOD and ADMS

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# EXECUTIVE SUMMARY

This report reviews inter-comparison studies of the new generation dispersion models: the USEPA's AERMOD and the UKADMS models. The main concern has been with the relative performance of AERMOD and UKADMS with each other and with the USEPA ISC and the UK R91 models which have been in common use for regulatory purposes in the UK but are now being replaced by the new generation models.

There have been relatively few model inter-comparison studies of this sort since the introduction of ADMS around 1991/2. Most studies have been concerned with the comparison of single models with field data. Such validation studies are an important feature of model development but are not a good guide to the differences between models. Field data is invariably highly variable and it is only possible to compare models on a basis of bulk statistical parameters which do not readily reveal the detailed reasons for differences between model dispersion calculations. The latter information can only be readily obtained from systematic parametric studies aimed at revealing differences between the different facets of model calculations such as basic rates of dispersion, plume rise, interaction with the top of the boundary layer, building entrainment and topography.

Only ten studies were found directly comparing either ADMS and AERMOD with each other or with the older models. Only four of these were of the systematic parametric variety. Some critical differences between the models are apparent in the studies but they are individually generally of limited extent and leave many matters un-investigated. The effects of building entrainment and topography in particular have been little studied. The literature is also constrained in that little of it is peer reviewed and a significant part of it is not readily available. Little attention has been given to variant versions of models issued over time and any differences between them. A critical feature of inter-comparisons appears to be the handling of meteorological data inputs to the models, especially in the relationship between Monin Obukhov length scale based inputs and Pasquill/Gifford stability categories.

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

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# 1. INTRODUCTION

Dispersion models are used for many purposes, but one of the most important is as an indicator of ambient pollution levels for regulation and control purposes. Regulation is usually by one of two approaches, by controlling pollutant emissions directly or by setting limits on the acceptable levels of airborne pollutants. These limits may be by setting probabilities of combinations of contaminant concentration and exposure time, as is done, for example, with risk assessment studies for toxic or flammable gas releases from industrial accidents. Alternatively, there may be statistically-based exposure limits in various forms, as with the regulation of controlled emissions of the common pollutants. These usually take the form of a number of limits applied simultaneously. For example, in the case of sulphur and nitrogen oxides in the UK, there are limits (DoE(1996)) based on annual average concentrations as well as a number of upper bound percentile concentration limits set for different averaging times. These range between 15 minutes (the 99.9%ile sulphur dioxide limit) and 24 hours, and for both 100%ile and 98%ile hourly averaged limits. There are also annual limits set for deposition of sulphur and nitrogen oxides to the ground to avoid exceeding critical acid loads for different species.

In regulatory applications the prediction of ambient concentrations and deposition using dispersion models directly affects any control procedures that may be required, by way of emission controls or of discharge stack heights for example, or even whether a process is authorised at all. The accuracy of models and any differences in behaviour between them then takes on a crucial importance and may affect substantial levels of expenditure on commercial plant.

In practice the accuracy of dispersion models and their ability to predict dispersion behaviour will always be limited for a number of reasons. The models themselves are significant approximations to true dispersion behaviour and, even given a perfect dispersion model, prediction of the state of the atmosphere (on which dispersion behaviour critically depends) is also approximate. This is partly due to the limited availability of meteorological data and partly due to the natural variability of the atmosphere, either in a given, defined state or on a statistical basis from one year to the next. The subject has long been one of concern and discussion and in more recent years has led to a substantial research effort. However, it has been generally accepted that in principle these difficulties, though quantifiable to some extent, are unavoidable in practical models. The major effort in model development, besides extending the range of application, has then tended towards minimising systematic errors in calculation and in trying to define the degree of uncertainty associated with model calculations.

The regulator is thus left with a degree of uncertainty in this aspect of air pollution control practice. This is compounded by differences between different dispersion models used for the same task. This latter is a normal state of affairs and it is common for substantial differences to exist in nominally identical calculations between different dispersion models and between different versions of the same model. These can to some extent be avoided by proscription, requiring the use of single models for specific purposes. This is done, for example, by the USEPA with its ISC models, which are expected to be replaced by the newer AERMOD model in due course.

The regulatory authorities in the UK have never used proscription, preferring to allow applicants for authorisation and other forms of approval to submit cases using models they felt to be the most appropriate. There are good reasons for this approach, but it does leave the question of differences between models unresolved. Until relatively recently this deficiency had not caused excessive difficulty in the UK as most regulatory dispersion calculations had used single or similar models. Up to the early 1990's, most calculations used either the ISC models or the UK R91 model (Clarke (1979)), which were largely similar. Since then, the significantly more advanced UKADMS model (Carruthers et al (1994)), which was introduced into the UK in this period, has tended to become a de-facto standard in the UK, being the preferred model for major authorisation applications, so that use of a single model has largely prevailed. However, the more recent appearance of the AERMOD model, which is an advanced model similar in type to UKADMS, has left a more open situation. It has become increasingly likely that the regulatory authorities will be subject to applications from at least both of these models, and probably to a wider range of models, over time.

From a regulatory point of view, the differences in predictions between models and between different versions of the same model are of equal, if not greater, importance than their absolute reliability. These differences are often of significant scale and can directly affect regulatory decisions. Hall and Spanton (1999) show an example of the differences occurring between two recent versions of the UKADMS model and two choices of meteorological data. It seems surprising, therefore, that relatively few inter-comparisons of this sort are made. The papers of the last three harmonisation meetings, at Mol (Cosemans and Maes (1995)), Ostend (Kretschmar and Cosemans (1997)) and Rhodes (1998, to be published) were mainly concerned with validation against field data and with the problems of handling and standardising dispersion and meteorological data. These matters are important in their own right, but should not preclude comparative studies. It may be argued, rightly, that comparisons of different models with the same field data represent such model inter-comparisons. However, as these are tied to the limited range of conditions prevailing in the field experiment, they do not usually allow systematic evaluation of the most important facets of dispersion so that differences between models can be clearly shown. This is discussed in more detail by Hall and Spanton (1999).

In order to attend specifically to the regulatory aspects of dispersion model behaviour, the Environment Agency's National Centre for Risk Analysis and Options Appraisal has commissioned an evaluation of the UKADMS and USEPA AERMOD models for regulatory purposes. The evaluation is to consider the strengths and weaknesses of both models in regulatory applications and the best options for their practical use. It is also to include the older USEPA ISC models, as a base case against which to compare the newer models. The intention of the study is to examine differences between the models rather than their absolute veracity. The latter is already the subject of study (and publication) by model developers and others as part of the model validation process and the greater need at present is in assessing the regulatory problem of differences between models. Part of the study is to produce a protocol for model inter-comparison, which can act as a set of test cases to be used for assessing changes in models and versions of models over the longer term. The methodology for this is discussed in Hall et al (1999).

The present paper is the initial review of previous inter-comparison work for the study. It has concentrated on work in which calculations for two or more models are compared, whether against experimental data or some assumed common meteorological or topographic conditions. There is also a bibliography (Appendix A) which gives the majority of the papers that could be found relating to AERMOD, UKADMS, R91 and the ISC models and which provided technical descriptions of the models and validation studies against experimental data, as well as any model inter-comparison studies. Only those most directly related to this review are referred to here.

Overall there are relatively few model inter-comparison studies compared with the total number of papers (over 100) in the bibliography and with the number of model validation papers using experimental data. Most are related to UKADMS, partly because of its longer availability (AERMOD has been available for about the last 18 months) and derive from the UK.

# 2. INTER-COMPARISON STUDIES

## 2.1 Jones et al (1995)

The first inter-comparison study to appear using the UKADMS model was that of Jones et al (1995), which compared ADMS (an early version, 1.06, which calculated dispersion for single meteorological states) with models using the NRPB R91 model (Clarke(1979)), at that time the most commonly used basis for UK dispersion studies. The report discussed differences between the physics of the two models in some detail. It noted that, though the ADMS model remained a gaussian model, nearly all aspects of the newer model, rates of dispersion, plume rise and building entrainment behaviour were different. In particular, the effects of boundary layer stratification were no longer directly related to the Pasquill/Gifford stability categories used in the R91 and EPA models, but to the Monin-Obukhov length scale. Also, for the first time, the boundary layer depth was computed directly instead of using a fixed value related solely to Pasquill/Gifford stability category. A critical component of the ADMS model was the meteorological data processor, which determined these and other essential input parameters to the model from standard meteorological data.

The study compared four main characteristics of the two models: basic rates of dispersion, plume rise, building entrainment and particle deposition. Figure 1 is a composite of three figures from Jones et al, showing differences in basic rates of dispersion of a neutrally buoyant plume in unstable (Category B), neutral (Category D) and stable (Category F) stratification for sources at three heights. Equivalent values of the Monin-Obukhov length scale were determined for use with the ADMS model; this is discussed further in relation to Bugg's work. The surface roughness, $z_0$, for the study was set at 0.3m. The plots are of plume centreline ground level concentrations with distance; students of the Bruce-Turner Workbook (Bruce-Turner(1994)) will recognise the method of presentation. The report notes the more marked effects of stratification on dispersion rates in the ADMS model compared to the R91 model; the former produced much greater vertical dispersion rates in unstable atmospheres and much reduced dispersion rates in stable atmospheres. Figure 1 shows these differences clearly. In the unstable and neutrally stable atmospheres the distribution of concentration with distance followed a similar form, the main difference being in the position and magnitude of the peak concentration. Overall, the ADMS model produced lower maximum concentrations than the R91 model at shorter distances from the source. The differences in concentration were relatively small in the plot for the unstable boundary layer and very marked for the higher sources in a stable boundary layer. In this latter case the point of maximum concentration was further from the source using the ADMS model. It must be noted that the scales in Figure 1 contain six decades of concentration vertically and four decades of distance horizontally, so that the differences between the models, though apparently small in some cases, are significant. Maximum ground level concentrations in the neutrally stable example (the centre plot) were different by about a factor of two between the models and differences in the distance to the maximum ground level concentration were of the same order.

Figure 2 shows, again, a composite of three figures from the original report for comparisons of particle deposition, the effects of plume rise and of building entrainment, all in a neutrally stable atmosphere.

Deposition calculations are shown on the left-hand plot of Figure 2, for a discharge from a 10m stack. Jones et al noted the marked differences in deposition between the two models and especially that the ADMS model showed no difference in deposition between 1 μm and 10 μm particles. Since the deposition relies on an assumed deposition velocity applied to the calculated concentration at ground level the differences between the deposition plot (the left hand plot of Figure 2) and the related ground level concentration plot (the centre plot in Figure 1) are mainly related to these deposition assumptions. The report is not perfectly clear at this point, but it appears that the ADMS model was provided with full (discretised) particle size distributions based on 1 μm and 10 μm median values while the R91 model was fed with single particle deposition velocities for 1 μm and 10 μm particle sizes. The particle deposition velocities used in the ADMS model are not given. Particle deposition velocities are not precise factors, they depend upon such things as the type of surface and their choice is to some extent a matter of individual opinion. Present versions of ADMS allow a user choice of deposition velocity as well as supplying default values. It is not clear how this comparison would have appeared had identical deposition velocities been used for both models.

The effects of release buoyancy and stack height are shown in the centre plot of Figure 2 for combinations of two stack heights, 30m and 70m, and two heat releases, 1MW and 10MW. Differences between the models were greatest with the 10MW heat release, those with the 1MW release appearing relatively slight. The ADMS model produced maximum concentrations closer to the source, as with the passive releases, but overall differences between the models were smaller. It appears that to some extent differences in both rates of dispersion and plume rise between the models were compensating one another. The R91 model calculations used the Briggs plume rise model. The ADMS model has a more complex, recursive, plume rise calculation in which the plume rise depends on the rate of dispersion.

The effects of building entrainment are shown in the right hand plot of Figure 2, for a discharge on the roof of a building of 60m height and three widths, 20m (a tall, narrow building), 60m (a cubical building) and 180m (a low, wide building). The R91 model produced well ordered curves with the maximum concentration in inverse proportion to the building cross sectional area. Further downwind the concentrations did not distinguish the effects of building shape. The ADMS model produced maximum concentrations in the building wake of a similar order, though lower, than the R91 model, but showed order of magnitude fluctuations in concentration at distances between 50m and 300m behind the building, before falling monotonically with increasing distance.

The R91 model used Barker's(1982) virtual source model, which shifts the source upwind by an amount designed to account for the enhanced lateral dispersion in the building wake. The ADMS building entrainment module uses a quite complex procedure which partitions the plume between building entrained and unentrained parts and modifies the rate of vertical dispersion to account for enhanced turbulence in the flow field downwind of the building. Sources outside the building wake may only be partially entrained. With a source on the building roof, complete entrainment of the discharge would normally be expected. Generally for this sort of discharge/building arrangement, experimental evidence is that for buildings square on to the wind the fall in concentration with downwind distance is relatively smooth and well ordered, following the R91 type of distribution. It seems possible that the ADMS calculations were showing some effect of plume partitioning and the type of variation in concentration close to the source that this discretisation can produce.

Jones et al concluded from their study that the ADMS model generated plumes that expanded vertically more rapidly in unstable flows and more slowly in stable flows than the R91 model. As a result, the maximum concentration was closer to the source in unstable flows and further away in stable flows than from the R91 model. In some cases the resultant differences in ground level concentration predicted by the two models were very marked. Overall, maximum concentrations tended to be different by a factor of 2-3 between the models. Such differences might be expected between a newer, more advanced model and an older, more basic one and were not, per se, reasons for criticism. However, they did feel that a number of features of the ADMS model required attention due to the unlikely nature of the results that it produced. Amongst these were a failure to account for wind direction meandering at long times, anomalous predictions of particle deposition and an unusual prediction of concentrations in the near field behind building wakes.

### 2.2 Bugg (1995)

At about the same time as Jones et al reported their work, Bugg (1995) published an MSc Thesis which also contained an inter-comparison study between two conventional gaussian models, the CEGB ALMANAC model and the PLUMES model, and ADMS version 1.05 (issued in 1993). Both ALMANAC and PLUMES are based on the NRPB R91 model dispersion rates and were in common use. Bugg's dispersion studies were concerned with relatively tall isolated stacks with buoyant releases, related to typical municipal waste incinerator and large generating station practice.

An important factor in the inter-comparison process noted by Bugg was the sensitivity of the calculation to the choice of meteorological conditions used to match the Monin-Obukhov length scale (used in the ADMS model) to the Pasquill/Gifford categories (used in the earlier models). Bugg tried two optional matches, labelled ADMS-1 and ADMS-2 respectively, shown in Table 1. The left hand set of data were from a note provided by CERC and were used by both Bugg and by Jones et al. In practice the relationship between the Pasquill/Gifford category and the other parameters is neither precise nor fixed. There is a strong dependence on surface roughness (see Golder (1972), for example) and a given Pasquill/Gifford category will correspond to a range of values of the Monin/Obukhov length scale ($L_m$). The right hand data set in Table 1 were derived by Bugg as being within the range of possible values. The left hand data set appears to be consistent with a surface roughness, $z_0$, of about 0.1m, as used by Bugg. Jones et al used a surface roughness of 0.3m for their study but did not appear to appreciate the need to modify the values of $L_m$ appropriately. Bugg's values of $L_m$ for ADMS-2 are on the extreme range of what is probable, but not impossible.

The results of Bugg's comparison for the two meteorological data sets are shown in Figure 3, which is a composite of three of Bugg's individual figures for unstable, neutral and stable conditions. The plots are of loci of the maximum ground level concentration against its distance from the source and each plotted point represents a result for one stack height, for which there is a matching value on the other curves. They are effectively plots of the position and value of the peak concentration from plots like those of Figures 1 and 2. It can be seen that the effects of Bugg's choice of $L_m$ has had only a limited effect in the near-neutral stabilities (where $L_m$ is large and its effect on dispersion relatively slight) but a much greater effect in unstable and stable boundary layers. There are no results for stack heights above 80m in the stable case as the plume was above the boundary layer. Overall the greatest effect appears to have been in modifying the downwind distances to maximum concentration. However, the differences in maximum ground level concentration were significant.

**Table 1. Relations between Pasquill/Gifford categories and Monin/Obukhov length scale used in Bugg and in Jones et al inter-comparisons.**

| Pasquill/Gifford Stability Category | ADMS-1 (Bugg), and Jones et al | | | ADMS-2 (Bugg) | | |
|---|---|---|---|---|---|---|
| | Wind Speed (m $s^{-1}$) | $1/L_m$* (m) | Boundary Layer Height (m) | Wind Speed (m $s^{-1}$) | $1/L_m$* (m) | Boundary Layer Height (m) |
| A | 1 | -0.5 | 1300 | 0.625 | -2.5 | 1300 |
| B | 2 | -0.1 | 900 | 2 | -0.147 | 920 |
| C | 5 | -0.01 | 850 | 4.12 | -0.0224 | 840 |
| D | 5 | 0 | 800 | 4.12 | 0 | 500 |
| E | 3 | +0.01 | 400 | 3.4 | +0.005 | 400 |
| F | 2 | +0.05 | 100 | | | |
| G | 1 | +0.2 | 100 | | | |

Not Used by Bugg

* $L_m$ : Monin/Obukhov length scale

Bugg's comparisons showed variable differences between the three models. One example is shown in Figure 4, of maximum concentration and its distance from the source for different discharge temperatures from an 80m stack. The curves are through groups of data for the same model and stability category and plot the loci of the maxima and their distances for different stack exit temperatures (and therefore of plume buoyancy). Differences between these two model calculations were quite marked for both stable and unstable stability categories, especially in the downwind distance to the point of maximum concentration.

Figure 5 shows results of two of Bugg's case studies, plotted as ground level concentration against downwind distance. The plots are the same as those of Jones et al but the axes are switched. Case Study 1, in the upper plots of Figure 5, is for a 91m stack with 9.3MW heat release, consistent with the discharge from a large municipal incinerator for example. Case Study 6, on the lower plots in Figure 5, is for a 198m stack with 210MW of heat release, consistent with the discharge from a major generating station. The pair of plots in each case study are of the annual average concentration on the left and for the single hourly weather condition producing maximum ground level concentration on the right. All the calculations showed marked differences between the models, including between the two R91 based models. Bugg remarked in this case that the differences are probably mainly related to the way in which the two models treat penetration of the boundary layer. The ALMANAC and ADMS models permit this, the PLUMES model does not. There are a few consistent patterns in the comparison. On some occasions the models produced quite similar results and in others major differences. Differences tended to be greatest in stable and unstable stratification, while similarities were generally (but not consistently) associated with neutral stratification. For lower stacks the two R91 based models tended to produce similar results. Also, in the four examples of Figure 5, the ADMS 1.06 model persistently showed higher maximum ground level concentrations closer to the stack than the other two models. Bugg remarked on this being a general feature of the comparison. In some cases, in unstable stratification, the ADMS model produced the maximum ground level concentration within one stack height distance from the source. Bugg also noted that this feature of the ADMS model had been modified in later versions so that the dispersion to the ground was less rapid in unstable stratification.

Bugg commented in his work on the difficulties of setting up precisely similar dispersion calculations between the models, including discretisation of the software and different model implementations. Grid resolution had, for example been found to be important in the ADMS model. He noted that the differences between the models revealed in his comparison were highly significant from a regulatory point of view and that more careful assessment of differences between models was desirable. He also commented on the importance of validation studies and on the importance of reliable test data sets for model validation (since attended to by Olesen(1995) and others). Finally, he pointed out the lack of reliable independent guidance on the use of models and their reliability, and also on the lack of information on differences between model calculations, all matters which directly affected their regulatory use.

### 2.3 The HMIP ADMS validation study (Carruthers et al (1996))

This study was commissioned by HMIP's National Centre during the course of Bugg's work. Its aim was both to compare the most recent version of the ADMS model (by this time version 1.35) with the R91 model and the USEPA ISC2 model, the then current ISC model. The version of the R91 model used was the CERC DISTAR model, which exactly reproduced the NRBP model together with Brigg's plume rise formulae (from the R91 (Clarke (1979)) and R157 (Jones (1983)) reports). The basis for the comparison was relatively recently acquired LIDAR data on plume rise and dispersion, which had not previously been used for this purpose. Though the aim was to compare the models with experimental data, the study still represented a model inter-comparison, within boundaries constrained by the data. The full report had a limited circulation, but a shortform (Carruthers et al (1997)) appeared in the fourth Harmonisation Workshop at Ostend.

Two main databases of LIDAR measurements were considered. The first was of large generating station plumes, partly collected by the CEGB and continued subsequently, using the same rapid scanning LIDAR, by M. Bennett of UMIST. The second source was a variety of dispersion situations, mainly at smaller scales, collected by the NPL differential absorption LIDAR. After considering the two data bases, five data sets were chosen as a basis for the model comparison exercise. The report's Table 4.2.3, which lists the data sets, is reproduced in Table 2.

It can be seen that four of the chosen data sets were for tall stacks with high buoyancy discharges (they are all from large generating stations) capable of producing plumes which would rise to the top of the boundary layer. The fifth was a neutrally buoyant discharge close to the ground. The main part of the study was thus effectively concerned with dispersion from tall stacks.

There were a substantial number of individual data sets from each site, so that ensemble statistics for the data could be produced. The inter-comparison used Hanna et al's (1991) BOOT software for evaluating statistically variable data in some cases. The work also gave detailed attention to determining the state of the atmospheric boundary layer in the data sets and to an adequate procedure for quality control and audit trails in the work programme.

**Table 2. LIDAR data test cases for Carruthers et al (1996) inter-comparison study.**

| Site | Release Height (m) | Thermal Emission (MW) | Topography | Scanning Plane | Sampling Period (min) | Number of Data Sets |
|---|---|---|---|---|---|---|
| **R3** | 259 | 280 | Flat | y-z (250<x<1300m) | 30 | 76 |
| **R4** | 210 | 95 | Estuarine | y-z (250<x<1100m) | 30 | 11 |
| **R5** | 122 | 60 | Flat | x-z (y~0) | 15 | 69 |
| **R6** | 137 | 100 | Flat | x-y (z~40m) | 10 | 23 |
| **D7** | 12 | -ve | Moorland | y-z (0<x<200m x-z (line of sight) | 10 | 9 from>90 |

The study contains excellent descriptions of the different models (including a long section on the ADMS model technical background), on the differences in the meteorological data they required and the reasons for this. In particular the study discusses relating Pasquill/Gifford based stability criteria to those using Monin/Obukhov length scales. Unfortunately, the inter-comparison itself is less clear and the figures and data are often difficult to interpret as they are not well discussed. For example, the importance of taking wind speeds at a height related to the dispersing plume is noted in the introduction, but its use in practice is less clear and there is reference to using 10m wind speeds for the R91 model. The effect of this on the inter-comparison is not always discussed.

The different data sets were used to compare different model parameters, depending on the field data available, and were presented in a variety of ways. The three models were not fully compared with each data set and the greatest interest was in differences between the ADMS and R91 models. Some examples of the inter-comparison with the R6 data set are shown in Figures 6 and 7. Figure 6 shows plots of plume height for the ADMS and R91 models. The upper plots are of calculated plume rise (the ADMS calculation gives both mean plume height and plume centreline) for two methods of assessment of the stratification, using surface heat flux or using date (and therefore insolation) and cloud cover. The lower curve in this latter plot is that of the R91 model and is the only example in the comparison where there is a significant difference between the models; in general plume height calculations for the two models were indistinguishable within the tolerance of calculation. The crosses on the two upper plots are of the LIDAR plume measurements; there are only a few of these but they seem consistent with the calculated plume rises. The lower plots on Figure 6 are of measured (LIDAR) against calculated plume height for all the data. Differences between the model calculations are relatively small and both models underestimated the higher plume rises, probably because the plume rise terminated near the top of the boundary layer. Figure 7 shows three examples of centreline ground level plume concentrations, for LIDAR measurements relatively high, low and close to the model calculations. The few small crosses on the figures are, as before, the LIDAR data. The only clearly visible line is that for the ADMS model and the pronounced vertical bars are estimates, using the ADMS fluctuations model, of one standard deviation of the possible range of concentrations. Concentrations calculated from the R91 and ISC models are low on the plot axis, predicting much lower concentrations than the ADMS model, but fall within the ADMS estimates of one standard deviation of the data range. They are difficult to see on the plot: a log scale would have been helpful. It can be seen from these examples that the differences in the comparison are large, but overall the ADMS model produced concentrations closer to the LIDAR data. The report attributes these differences between the models mainly to the method of determining the stratification. The ground-based procedures of the R91 and ISC models predicted neutral stratification, while the ADMS meteorological input model predicted a convective boundary layer.

Figure 8 shows examples of comparisons of calculated plume rise and plume spread from the ADMS and R91 models against the R3 data set. The R91 data is grey-shaded, the ADMS data is black. The stratification estimates were based on heat flux. For both plume rise and spread the ADMS model gave estimates on and above the 1:1 line and the R91 model gave results on and below the line. Statistical box plots, following Hanna et al's (1991) BOOT procedures were produced for this comparison and some examples are shown in Figure 9, matching the plots of Figure 8. These use Monin-Obukhov length scaling for the plot axis; equivalent plots using Pasquill/Gifford categories are given in the report. Though the choice of axis does not affect the statistical differences, the report notes that the determination of atmospheric stability differed between the models. The ADMS model calculations ranged between neutral and unstable, while the R91 calculations were all for neutrally stable flows. Figure 9 shows statistically the differences observable in the scatter plot of Figure 8, that the ADMS model tended to overestimate the plume height and spreads, while the R91 model tended to underestimate these quantities. Overall, statistically the ADMS model calculations were closer to the field data.

Figure 10 shows scatter plots of plume rise, lateral and vertical spread for the ADMS and R91 models for the R4 data comparison. There were no BOOT statistics plotted in this case, though some were tabulated. There is less LIDAR data than with the R3 site, but overall the two models showed the same sorts of difference as the previous comparison, with the ADMS model tending to overestimate the dispersion and plume rise and the R91 model tending to underestimate these quantities. Overall the ADMS model gave the better fit to the data.

Figures 11 and 12 show scatter plots and BOOT statistics for the R5 site data for plume rise and vertical plume spread, for stability based on heat flux. The data in Figure 11 is scattered and within this there appears to be little difference between the models' estimates of plume rise. The vertical plume spread was again mainly overestimated by the ADMS model and underestimated by the R91 model, but the distinctions were less than with the previous test cases discussed and both models had significant numbers of both over- and under-predictions. The related BOOT statistics in Figure 12 show this, with little statistical difference between estimates of plume rise and similar relative over- and under-prediction by the ADMS and R91 models respectively.

The final data set, D7, was the small-scale short range dispersion study at Spadeadam which was quite distinct from the other data sets. Figure 13 shows plots of plume centreline lateral concentration distributions from the ADMS and R91 models and LIDAR data at two source distances, 40m and 80m. Some of the original detail is lost in this plot (but only a little, the original is in an unfortunate choice of colours) but the essential features are visible. These are that both models significantly over-predicted the plume spread and peak concentration obtained by the LIDAR, the ADMS model by the greater amount. The report questioned the reliability of this data set as the plume path was uncertain (the release was slightly heavier-than-air and appeared to fall to the ground, though not within the 80m distance of the data in Figure 13) and the rate of release of the trace gas (a nitrogen/methane mixture) was queried. The spatial resolution of the LIDAR (about 5m) was also large compared with the scale of the dispersion at the short ranges used.

Overall this study provided a number of useful insights. The first was that there was a significant and growing amount of useful LIDAR data for this sort of comparison, without which the behaviour of buoyant plumes high in the boundary layer is hard to measure. The second was that calculations of plume rise by the three models were (in the tall stack cases) mostly indistinguishable within the order of accuracy to which this type of calculation is feasible. The third was that there were significant differences in rates of dispersion between the models in the neutral to unstable flows represented by most of the field data. The ADMS model generally gave significantly higher plume spread rates than the R91 model. Also the ADMS model tended to overestimate plume spread rates from the data sets and the R91 model to underestimate them. Overall the ADMS model was the better fit to the tall stack data sets. The fourth was that, as noted by Bugg, model calculations were heavily dependent on choices of the state of the atmosphere, especially of the stability. In two of the test cases the R91 model ground-based stability parameters indicated neutral stability while the upper atmosphere was unstable according to the ADMS meteorological input module calculations. These differences resulted in cases where the ADMS model was run assuming a convective boundary layer, while the R91 model assumed neutral stability. Some of the differences between the model comparisons (for example the single case in Figure 6 where the ADMS and Briggs' plume rise calculations disagreed) seem to be attributable to this cause.

### 2.4 Maul et al (1996)

Maul et al (1996) carried out a study of dispersion models for Integrated Pollution Control for HMIP. The primary purpose of the study was to relate the Inspectorate's main integrated assessment tool at that time, the APPRAISE model (a multi-faceted model whose air dispersion component was essentially the R91 model), with both the ISCST2 (the BREEZE version), ADMS (version 1.5) and DISTAR (another R91 clone) models. Applications for authorisation were being submitted to the Inspectorate using all of these models and there was no guidance as to what differences might exist between them. The report discussed a wide variety of available dispersion models and the differences between them in some detail. It mainly concentrated on the five models noted above, especially in relation to the newer ADMS model and carried out a number of sample comparative calculations aimed at exposing any differences between them. It selected eighteen representative meteorological conditions and carried out dispersion calculations for the five models for buoyant and non-buoyant discharges from 20m and 200m discharge stacks. The calculations were all at relatively low wind speeds, of 1, 3 and 5 $ms^{-1}$.

The model calculations were mainly presented in tabular form. These are difficult to assimilate, but three sets of data were plotted and are reproduced in Figure 14. The plots are of concentration at a fixed distance of 10km (though the tabulated data also gives results for 1km distance), using the APPRAISE model data as a reference on the axis. The vertical scatter in data for the three other model results plotted essentially represents differences between them for fixed calculation conditions. The upper plot is for a 20m source height without plume rise, the middle plot for a 20m source height with plume rise and the lower plot is for a 200m source height with plume rise. In the three plots most of the DISTAR model calculations are close to the 1:1 line, though there are some significant deviations. The ADMS calculations generally produced lower concentrations than APPRAISE and the BREEZE model produced both lower and higher concentrations. As the plotted concentrations were given at fixed distances, they do not show how the maximum values of the calculated concentrations compared. These are known from the earlier work discussed to vary considerably between models. Values are tabulated in the report and vary up to a factor of four. The report also discusses calculations of longer-term average concentrations, but these were estimated on a weighted basis using the single conditions previously calculated rather than using a year's hourly data.

In its conclusions, Maul et al's (1996) report discussed the differences between the models. It noted the importance of the plume rise calculation as well as the dispersion calculation to the ground level concentrations, and attributed differences between the APPRAISE and DISTAR models (both R91 based) to differences in the plume rise calculation. Though the BREEZE model is similar to R91, the precise dispersion rates and methods of accounting for surface roughness are not the same. Differences between the BREEZE model and the APPRAISE and DISTAR models were attributed mainly to this cause. Ground level concentrations calculated with these models generally agreed to within a factor of three. Differences between the ADMS model and the other models were attributed to different calculated rates of dispersion and other factors. The report noted the marked differences in dispersion behaviour between the other models and ADMS, which produced significantly more rapid vertical dispersion in convective conditions and reduced dispersion in stable conditions. This considerably altered the distances at which maximum ground level concentrations occurred. Overall the older models produced individual maximum concentrations which differed by up to a factor of three and with the inclusion of the ADMS model by up to a factor of four. Longer-term averages were generally more stable, being similar to one another within a factor of 2-3.

## 2.5 Harvey (1998)

Harvey (1998) showed some of the first inter-comparisons between the ADMS model (version 2.2) and the then newly available AERMOD models towards the end of 1998. Some of this work, related to building entrainment, is discussed later in this review. There has also been an unpublished presentation of some calculations of annual statistics for four examples of practical discharges, two of which were repeated using complex terrain (using only the AERMOD model). Since the results are not readily available the main data is reproduced here. Data for the four test cases is given in Table 3. They are for buoyant discharges from stacks of heights between 50m and 120m. In two cases there is a building, though too low to have greatly affected the calculation. Cases 2 and 4 were recalculated using complex terrain. The four cases were run using the relevant local meteorological data.

One representative set of Harvey's plotted data is shown in Figure 15, which gives contour maps for the two models of the annual average concentration and the maximum (100%ile) hourly concentration. Also shown in the figure is a plot of the maximum values of the different percentile concentrations. The annual average concentration contours for the two models are similar in character but not identical. The maximum values are of a similar order and in similar regions. The 100%ile contours for the two models both show multiple-lobed contour patterns radiating from the stack, but there are significant differences in both the contour patterns and the values of the maxima. These multi-lobed patterns are a common feature of this sort of plot. They are to some extent an artefact of the model output, which gives constant concentrations over discrete arcs and this affects the contour mapping. The plot of maximum values of different percentile concentrations in the figure shows these differences clearly. Below the 99%ile the maximum concentrations of the AERMOD and ADMS model are similar, but the higher percentile values of the ADMS model increase markedly over those of the AERMOD model. Harvey's summary of his calculations is reproduced in Table 4. The differences between the model concentrations, divided by the mean values, have been added.

**Table 3. Details of Harvey's (1998) four test cases.**

| **Case No** | **1** | **2** | **3** | **4** |
|---|---|---|---|---|
| Description | CCGT | Cement | Bio Fuel | CCGT |
| Stack Height(m) | 70 | 120 | 50 | 55 |
| Stack Diameter (m) | 7 | 2.8 | 1.5 | 11.2 |
| $NO_x$ Emission (g $s^{-1}$) | 35 | 100 | 20 | 102 |
| Discharge Velocity (m $s^{-1}$) | 17 | 24 | 21 | 25 |
| Discharge Temperature (°C) | 90 | 100 | 165 | 95 |
| Building: | | | | |
| X(m) | 0 | - | -33 | - |
| Y(m) | 0 | - | 16 | |
| Length (m) | 25 | - | 49 | - |
| Width (m) | 18 | - | 20 | - |
| Height (m) | 35 | - | 28 | - |
| Angle (°) | 0 | - | 337 | - |

**Table 4. Summary data from Harvey's (1998) calculations.**

| Percentile | Model | Case Number | | | |
|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 |
| 100 | ADMS | 142 | 123 | 267 | 222 |
| | AERMOD | 31 | 114 | 234 | 62 |
| | Difference | 1.28 | 0.076 | 0.13 | 1.12 |
| 99.8 | ADMS | 58 | 69 | 245 | 41 |
| | AERMOD | 17 | 65 | 122 | 32 |
| | Difference | 1.09 | 0.05 | 0.67 | 0.25 |
| 99.5 | ADMS | 25 | 54 | 204 | 35 |
| | AERMOD | 15 | 51 | 101 | 27 |
| | Difference | 0.50 | 0.057 | 0.68 | 0.26 |
| 99 | ADMS | 15 | 43 | 190 | 30 |
| | AERMOD | 13 | 44 | 88 | 21 |
| | Difference | 0.143 | -0.023 | 0.73 | 0.35 |
| 98 | ADMS | 11 | 29 | 151 | 23 |
| | AERMOD | 10 | 36 | 72 | 12 |
| | Difference | 0.095 | -0.22 | 0.71 | 0.63 |
| Annual Average | ADMS | 0.66 | 1.56 | 7.55 | 1.47 |
| | AERMOD | 0.64 | 2.12 | 5.69 | 0.9 |
| | Difference | 0.031 | -0.30 | 0.28 | 0.48 |

It can be seen in Table 4 that, with one exception, the AERMOD model produced lower concentrations than the ADMS model in all cases. There is no consistent pattern of the differences with the percentile value, though the largest differences tend to occur at the higher percentiles.

### 2.6 American Petroleum Institute study (Hanna et al (1999a,b))

This study is still in progress at the time of writing this review and is presently probably the major recent model inter-comparison study. It comprises a comparative study of the ISC3. AERMOD and ADMS (version 3) models against five field data sets. Of the five data sets, three (Duke Forest, Kincaid and Indianapolis) were for flat terrain, one (OPTEX) involved building entrainment (in a refinery complex) and one (Lovett Field) topography. The Duke Forest and OPTEX cases had low level sources, the others had tall stacks. The draft report (Hanna et al (1999a)) contains full details of the work, but there have been further studies and revisions to this which have yet to be published. The conference paper (Hanna et al (1999b)) contains a description of the field data sets and the comparison method (using Hanna et al's BOOT procedures), with a summary of the overall conclusions. A brief summary of these is given below. The bulk statistics for the comparison (Hanna et al's (1999b) Table 1) is reproduced as Table 5.

> OPTEX data set. This was the only data set involving severe building entrainment. One set of data used solid obstacles (oil tanks), while the other used the porous structure of the refinery plant. With the tank data, on average ISC3 over-predicted concentrations by about 15% while ADMS and AERMOD under-predicted by about 50%. However this mean value masked much larger variations in the near field, with differences up to a factor of eight, where building entrainment effects predominated. The mean model and field concentrations were usually within a factor of two.

With the porous plant structure all the models over-predicted maximum concentrations, ISC3 by a factor of 10, ADMS and AERMOD by a factor of 3. On average for this data set, ISC3 over-predicted by a factor of two, ADMS and AERMOD performed similarly, over-predicting by about 10%. The paper notes the problems of accounting for downwash behind porous structures in any of the models.

Duke Forest data set. This used low sources in a forest clearing with no obstructions. ISC tended to over-predict the measured concentrations (both mean and maximum) by about a factor of three, ADMS and AERMOD tended to under-predict, though by lesser amounts up to a factor of two, and had broadly similar performance.

Kincaid data set. This had 187m high sources in uniform low roughness terrain. All three models under-predicted the maximum concentration (by 30-50%) and only AERMOD predicted its position well. On average ADMS predicted the data set quite closely (within 3%), AERMOD under-predicted by about a factor of two and ISC3 by a factor of five. These average results include a high variability in the comparison, observations within a factor of two of the observed were 44% for ADMS, 29% for AERMOD and 12% for ISC3.

Indianapolis data set. This had an 84 m stack in rough (suburban) terrain. All three models predicted the maximum concentration fairly well, with some over-prediction. All models under-predicted the distance of the maximum concentration (6km), ADMS and AERMOD by a substantial amount (0.5km and 1 km respectively). The quality of agreement depended on the source distance, with AERMOD and ISC tending to under-predict at short ranges and over-predict at long ranges. ADMS over-predicted at short ranges and under-predicted at intermediate ranges.

Lovett data set. This had a 145m stack in pronounced topography, rising 200m above the stack. This data set had been used previously as part of the AERMOD validation set, so this model was to some extent calibrated against the data. The ISC model over-predicted the maximum concentration by a factor of ten, AERMOD was very close (within 1%) and ADMS under-predicted by 40%. The report also noted biases in the data comparison. ADMS and AERMOD were within a factor of two of the field data for about 30% and 25% of the time respectively. There were a number of complications with this data set comparison besides the AERMOD model having used it for its basic validation. The version of ADMS used did not account for the terrain and the calculations are due to be repeated with the ADMS terrain module, FLOWSTAR. The ISC model defaulted to the EPA COMPLEX-1model which handles large terrain.

**Table 5. Overview of model evaluation results for ISCST3, ADMS and AERMOD for arc max[1] for the five field sites. From Hanna et al (1999b).**

| Data Set | No. Samples | Max Concentration Observed | Maximum Concentration | | | Geometric Mean (or Fractional Bias) | | | Geometric Variance (or Normal Mean Standard Error) | | | Fraction Within x2 of Observed | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | ISCST3 | ADMS | AERMOD | ISCST3 | ADMS | AERMOD | ISCST3 | ADMS | AERMOD | ISCST3 | ADMS | AERMOD |
| OPTEX (Tank) | 10 | 3,080 | 25,850 | 1,121 | 1,091 | 0.86 | 2.12 | 2.47 | 2.8 | 3 | 4.4 | 0.8 | 0.8 | 0.7 |
| OPTEX (Plant) | 25 | 152 | 1,567 | 469 | 502 | 0.55 | 0.89 | 1.02 | 2.9 | 1.59 | 1.8 | 0.64 | 0.76 | 0.76 |
| Duke Forest | 89 | 468 | 1,660 | 440 | 251 | 0.32 | 1.41 | 1.830 | 11.6 | 1.7 | 2 | 0.17 | 0.63 | 0.53 |
| Kincaid | 473 | 319 | 175 | 211 | 152 | 1.33 FB[2] | -0.03 FB | 0.75 FB | 8.5 NMSE[3] | 0.7 NMSE | 2.2 NMSE | 0.13 | 0.59 | 0.29 |
| Indianapolis | 777 | 5,379 | 6,780 | 5,736 | 6,076 | 0.85 | 1.14 | 1.54 | 6.8 | 5.6 | 13 | 0.49 | 0.42 | 0.39 |
| Lovett | 2,595 | 447 | 4,420 | 267 | 441 | -1.68 FB | 0.14 FB | -0.37 FB | 46 NMSE | 3.6 NMSE | 3.6 NMSE | 0.064 | 0.3 | 0.25 |

Arc max: Maximum concentration within the lateral arc of measurement (Irwin(1997)).
FB: Fractional Bias.
NMSE: Normal Mean Standard Error.

Hanna et al produced two overall summary scores for the models as a means of producing a simple performance measure. The first, Table 6, was a summary score of relative performance between the models for the cases tested. The last line, of ‘Best plus Middle’ has been added here. The nature of this type of inter-comparison is that it involves high levels of variability and the differences between ‘best’ and ‘middle’ are to some extent notional.

Hanna et al (1999b) noted that the scores shown in Table 6 did not indicate the scale of the differences between the models, which could readily be small or large, so they provided some additional bulk performance measures. These were collected values of some BOOT statistical parameters for all the field data comparisons, reproduced as Table 7.

Hanna et al’s conclusions from the study were that the two newer models, ADMS and AERMOD performed considerably better than the ISC3 model, but that the difference between the two newer models was less clear cut and their performance was of a similar order. Overall the ADMS model produced the highest scores in both Table 6 and Table 7, but the differences were not large in terms of the accuracy of this type of inter-comparison.

It is of interest that no model in the study was consistently good or bad and that all the models had a creditable performance for at least some of the data sets.

**Table 6. Hanna et al (1999b) summary scores of model performance.**

| | **ISC3** | **ADMS** | **AERMOD** |
|---|---|---|---|
| **Best** | 5 | 19 | 6 |
| **Middle** | 2 | 5 | 11 |
| **Worst** | 17 | 0 | 7 |
| **Best plus Middle** | 7 | 24 | 17 |

**Table 7. Hanna et al (1999b) median performance measures for all the field data comparisons.**

| | **ISC3** | **ADMS** | **AERMOD** |
|---|---|---|---|
| **$MaxC_p/MaxC_0$** | 6.7 | 0.80 | 0.77 |
| **Geometric Mean** | 0.70 | 1.22 | 1.70 |
| **Geometric Variance** | 7.7 | 2.4 | 2.9 |
| **Fraction within x2** | 0.33 | 0.53 | 0.46 |

## 2.7 Comparisons involving building entrainment

Building entrainment effects are an important feature of many practical dispersion problems and comparison studies have been relatively rare. The ISC and AERMOD models do not have formal building entrainment corrections, relying on ‘Flagpole Receptors’ above the ground to provide upper bounds to concentrations at the ground due to building effects. The ISC SCREEN model (but not ISCST3) has an entrainment model and the newer EPA PRIME model deals with building entrainment, though it is not formally accepted for regulatory purposes. The ADMS model has a sophisticated building entrainment model.

Barrowcliffe and Harvey (1998) and Harvey and Obasaju (1999) have examined the relationship between the building entrainment corrections in the different models and wind tunnel data. Both papers used the same experimental data and Harvey and Obasaju compared both the ADMS and AERMOD models with it.

The experimental data is not discussed in any detail, but this does not directly affect the model inter-comparison. The main results of the study are shown in Figure 16. The data is for two practical test cases which were subject to wind tunnel model testing and which had relatively low stacks compared with the building. One case was a cement plant and the other a CCGT station. There are two plots for each case in Figure 16, the upper plots are for maximum concentrations at the ground for different stack heights in the absence of a building, the lower plots are for a fixed stack height with the building for the full circle of wind directions. Without the building neither the two models nor the wind tunnel data agreed, except for the higher stacks on the cement plant, when the two models gave closely similar results. With the building the ADMS model showed a strongly cyclic variation of concentration with wind direction which was only slightly reproduced by the wind tunnel data. Both the wind tunnel and AERMOD models predicted much lower concentrations than the ADMS model. The wind tunnel and AERMOD model concentrations were within the order of accuracy that might be expected of such a comparison.

Hanna's inter-comparison with the OPTEX field data set, with dispersion from a low source surrounded by refinery plant, is discussed in the previous section.

### 2.8 AERMOD evaluation inter-comparisons

During the course of development of the AERMOD model, the AERMIC Committee carried out validation studies to match the AERMOD model to field data and made further assessments against other field data and other models, especially the ISCST3 model. Most of this work was published in the committee's evaluation reports (Paine et al (1998) and Peters et al (1999)).

The first of these reports (Paine et al(1998)) covered a total of ten data sets with both flat and hilly terrain. The latter are considered in the next section. Results for two sets of the flat terrain data, quantile/quantile plots for Kincaid and Baldwin, both tall stack discharges, are shown in Figure 17. The Baldwin case also included a comparison with the HPDM model. In both cases AERMOD outperformed ISC on this basis. Though AERMOD tended to underestimate the lower predicted concentrations, it predicted higher concentrations relatively closely. The ISC model tended to under predict concentrations, though its performance similarly improved for higher concentrations.

The second report (Peters et al(1999)) covered direct intercomparisons between AERMOD ISC and CTDMPLUS (the complex terrain dispersion model). The intercomparison included a range of discharge heights (from near ground to 200m), discharge buoyancies (neutral and very buoyant), source types (point, volume and area sources) and terrain types (flat, gentle and complex). The terrain cases are discussed below. The dispersion calculations were run for two representative sets of hourly meteorological data for urban and rural sites respectively. Figures 18 and 19 show bar charted results from Peters et al for a range of test cases. Figure 18 shows flat terrain results for the range of stack heights in rural (the upper plots) and urban terrain (the lower plots). The stack heights increase from left to right across the pairs of plots. Figure 19 shows results for a single 35m stack height for the range of test conditions, including simple topography. Both sets of data are for point sources and show ratios of concentrations for AERMOD/ISC for the maximum hourly, 3 hourly, 24 hourly and annual means in sets for each test conditions. Both Figures show marked variations in calculated concentrations between the two models with different stack heights and test conditions. Figure 18 shows that both switching from rural to urban terrain and meteorology and passing from low to high stacks reversed the relationship between the models.

Generally, differences in calculated concentrations between the models, for any averaging period, were significant with about one third of the differences exceeding a factor of two either way. The smallest differences between the two models, shown clearly in Figure 19, occurred with the 35m stack height in urban terrain and meteorology.

### 2.9 Comparisons involving topography

Accounting for topography in dispersion is regarded as an important matter. However, there are few papers involving model inter-comparison. There appear to be only six studies in the public domain which consider the performance of AERMOD in conditions involving complex terrain. The authors of three of these are members of the AERMIC committee, responsible for the development of the AERMOD model. In the studies, AERMOD is either evaluated directly using measured data or compared with other models commonly used to predict pollutant dispersion over complex terrain. There are no specific studies of ADMS in relation to the other models involving dispersion over topography besides that in Hanna et al's (1999a,b) recent study, described above and Harvey's(1998) unpublished work.

AERMOD has been designed to handle both flat and complex terrain within the same framework. It incorporates more current concepts about flow and dispersion in complex terrain which in this respect makes it more sophisticated than ISCST3, the existing USEPA regulatory model. ISCST3 uses the complex terrain screening algorithm, COMPLEX1, only to account for terrain effects. However, AERMOD is less complicated than CTDMPLUS, the refined regulatory model for complex terrain, and has been developed specifically to require less detailed meteorological and terrain inputs. AERMOD has been compared to both CTDMPLUS and ISCST3 (also referred to as COMPLEX1 below) in several studies (Garrison and Sherwell (1997), Paine et al (1998), Peters et al (1999), Venkatram et al (1998)).

Garrison and Sherwell (1997) considered developmental versions of AERMOD (1 to 4) and, in fact, it would appear that the finalised version of AERMOD considered in the present study is a combination of versions 3 and 4 (i.e. the terrain weighting factor has a minimum of 0.5 and height scales are calculated for each receptor). This illustrates one of the main problems with the assessment of dispersion models; they are constantly subject to change. However, a number of general points can be made from the report. Firstly AERMOD represents an improvement on COMPLEX1 because it responds better to continuously changing meteorological conditions. When maximum overall concentrations were considered (i.e. no spatial discrimination), for a given set of meteorological conditions, then the results of AERMOD and CTMPLUS were comparable. When the ability of the models to replicate the flow physics was examined it was found that AERMOD did not allow the plume to wrap around the terrain in the same way as CTDMPLUS.

The EPA model evaluation study (Paine et al 1998) used data from one dependent (Lovett, used in the AERMOD developmental model evaluation) and four independent complex terrain sites. The results are presented as the ratio of modelled/observed robust highest concentrations and quantile-quantile plots, both of which pair-ranked modelled and observed concentrations in value order, but which are unpaired in time and space. Hence the effect of particular terrain conditions on the overall distribution of concentrations is not considered and no account is taken of model physics in the assessment. The quantile-quantile plots for four of the site comparisons is shown in Figure 20. The results indicate that AERMOD performed better than ISCST3 but, more surprisingly, also out-performed CTDMPLUS, mainly underpredicting both models.

Since real field data were used in the evaluation, one factor, in addition to the assessment method, may be the relative inaccuracy of the detailed input data required by CTDMPLUS. The quantile-quantile approach was also employed to compare ISCST2, AERMOD and CTDMPLUS using the Lovett data set (Venkatram et al (1998)) and, again, AERMOD produced the best results and ISCST2 the worst. The importance of highest concentrations for regulatory purposes may explain the assessment methods applied in these studies.

Peters et al's study also included the effects of terrain and Figure 19 shows some examples for their 'simple' terrain. This study also included a larger range of more severe 'complex' terrain cases. No results of this study are shown here, but the AERMOD model produced consistently lower concentrations at the ground than ISC under almost all circumstances, in the great majority of cases by more than a factor of two.

### 2.10 Papers from the HARMO99 Conference

This conference has generated several papers containing model comparison data. Hanna et al's (1999b) paper has been discussed previously, but three other papers are of interest here.

Hill et al (1999) presented results of a comparison between the R91 and ADMS model in calculating dispersion over the UK BNFL Sellafield Reprocessing Site against measurements using a Krypton-85 tracer. This is discharged from two stacks of 122 and 125 m height in the plant at safe radiological levels, but makes a good tracer even at these low concentrations. The site was well instrumented meteorologically and care was taken to assess the atmospheric stability adequately using two different methods (eddy correlation and flux profile). About 70 tracer samples were taken from three sites around the plant over 24 hour periods. About 80% of the measurements were in neutrally stable atmospheres. Figure 21 shows the main results of the work, modelled against calculated concentrations for the two models. Table 8 shows the calculated BOOT statistics for the two comparisons.

**Table 8. BOOT statistics for R91 and ADMS model inter-comparison with field data from the Sellafield Site. From Hill et al(1999).**

| Model | Normal Mean Standard Error | Mean Bias | Correlation ($R^2$) % | Within factor of Two % | Within factor of Five % | Within factor of Ten % |
|---|---|---|---|---|---|---|
| R91 | 5.05 | 2.79 | 16 | 34 | 62 | 75 |
| ADMS | 10.31 | 4.58 | 11 | 35 | 56 | 73 |

Figure 21 shows only limited differences between the model comparisons, which Table 8 largely confirms. The R91 model showed the lower levels of mean bias and normal mean standard error. The level of agreement between the models and the field data is comparable to other studies described here. Hill et al concluded that it made little difference which model was used in this application. They also noted that the ADMS model tended to produce a maximum concentration nearer the source than R91, in common with other comparisons. The relative agreement between these two models in this case may be due to the relatively high frequency of neutral stability as the major differences between the two models appear to be in stable and unstable conditions.

A comparative study of the ADMS, OML and ISCST3 models and a local model (MADAM-MP) for a power plant discharge (from a 250m stack) was described by Kanevce et al (1999).

These were compared with 24-hour mean measurements of $SO_2$ recorded around the plant. The calculations were carried out in 24 one-hourly batches, to match the monitoring data and good surface meteorological data was available from a nearby source, 10km from the plant. However, there was a shortage of upper air data and boundary layer depths, though this is not unusual for modelling data. A feature of the local meteorology was the high frequency of low wind speeds, below $1ms^{-1}$, about 45% of the time. It was also estimated that the boundary layer was below the stack for about 50% of the time. Figure 22 shows scatter and quantile/quantile plots of the three model/data comparisons and Figure 23 shows comparisons of the three model calculations and the four monitoring site concentrations on a daily basis. The relation between observed and calculated concentrations seems tenuous in many cases. No bulk statistics for the comparisons were given. The conclusion of the study was that, considering the lack of mixing height data, the frequency of very low wind speeds and the low ground level $SO_2$ concentrations measured, the general standard of all the model calculations was good. This seems a slightly optimistic view. Overall the ISC model using the local meteorological pre-processor appeared to give the best results, though occasionally over-predicting concentrations. The OML model followed the trend of the data but tended to under-predict and the ADMS model followed the trend of the data but produced occasional predictions of high concentration when levels at the ground were low.

McHugh et al(1999) also described an inter-comparison between the ADMS 3, and the USEPA AERMOD and ISCST models, using the Kincaid, Indianapolis and Praire Grass data sets. The main purpose of the paper was to examine differences between two validation methodologies, the 'Maximum Arcwise Concentration' (MAC) procedure of Olesen's Model Validation Kit ('MVK', Olesen(1995)), as originally laid down by Hanna et al (1991) and a more recently developed ASTM 'Near Centreline Concentration' ('NCC', (Irwin (1997), Irwin and Rosu (1998)) procedure. McHugh et al remarked that results from the two analysis procedures will not be the same; NCC values derived from the field data will be lower than MAC data thus directly affecting any validation study. In some ways the differences between the two procedures appear statistically arcane and are only likely to be significant when there are high levels of scatter in the original data (which there is). For better-ordered data the differences would not be large. Besides comparing validation methods, the use of three models in this study also effectively provided a model inter-comparison. Figure 24, a composite of McHugh et al's figures, shows the fractional bias of the data comparison (from the Model Validation Kit, using Hanna's BOOT statistics) for the three data sets used, plotted against the 'Regime Number' (the 29 regimes defined in the ASTM methodology). McHugh et al remark that a value of the Fractional Bias of 2 means no correlation, a value of 1 means agreement within a factor of three of the field data and a value of 0.67 agreement within a factor of two. It can be seen that, on this basis, the level of comparison between the three models and with the field data is very variable. ADMS and AERMOD generally follow similar trends in the data with the ISCST3 model showing greater differences from the other two models. Some values of the comparison statistics are shown in Table 9. These are restricted here to the mean values and the Fractional Bias as only the latter figure is given for the ASTM data using MAC.

**Table 9. Comparison Statistics for ADMS, AERMOD and ISCST3 against three sets of field data. From McHugh et al (1999).**

| Field Data | Statistic | Observations | ADMS | | AERMOD | | ISCST3 | |
|---|---|---|---|---|---|---|---|---|
| | | | MVK | MAC | MVK | MAC | MVK | MAC |
| **Kincaid Quality 3** | Mean | 54.3 | 51.7 | | 21.8 | | 30 | |
| | FB | 0 | -0.051 | 0.46 | 0.86 | 0.49 | 0.58 | 1.99 |
| **Indianapolis** | Mean | 260 | 270 | | 230 | | 400 | |
| | FB | 0 | -0.029 | 0.52 | 0.14 | 0.34 | -0.44 | 0.87 |
| **Praire Grass** | Mean | 2.14 | 1.2 | | 2.14 | | 2.01 | |
| | FB | 0 | 0.57 | 0.56 | 0 | 0.40 | 0.064 | 0.94 |

Positive Fractional Bias indicates overestimation and negative Fractional Bias underestimation against the reference field data. It can be seen from the Table that estimates of Fractional Bias from the two analytical techniques are dissimilar except in one case. It can also be seen that the values of Fractional Bias published for the Kincaid data set used by both McHugh et al and by Hanna et al (shown in Table 5) are dissimilar. It has not been possible here to determine the cause of this difference, but Hanna et al's values are bracketed by the MVK and MAC values in Table 9. It appears that the method of calculating this statistic can considerably alter the apparent performance of the models. Table 9 shows a confusing pattern of model differences and the comparison overall is somewhat inconclusive. With the Kincaid data, AERMOD and ISCST3 are closer to one another than to ADMS, which appears, however, to be closer to the field data. With the Indianapolis data, ADMS and AERMOD are closer to one another than to ISCST3, except using the MAC Fractional Bias estimates. ADMS is the better fit to the field data using MVK statistics, but AERMOD is closer using the MAC statistics. With the Praire Grass Data (which, McHugh et al note, was used to calibrate the AERMOD model) AERMOD and ISCST3 are closer to one another (and to the field measurements) than to ADMS.

# 3. DISCUSSION AND CONCLUSIONS

In terms of the quantity of data presented here, most of the studies discussed here involve comparisons with field experiments. It was noted in the introduction that, though clearly very important, these are essentially a validation process which, because of the inherently high level of variability in such data, can only mainly indicate differences between models in terms of the bulk statistical parameters of the data fit. Though these can be aimed at specific dispersion problems, buoyant discharges from tall stacks or topography for example, they do not readily reveal why differences between model calculations occur. Thus with buoyant discharges from tall stacks, for example, it is not immediately clear whether differences between model calculations are due to differences in basic rates of dispersion, plume rise or in procedures used for interaction with, and plume penetration of, the top of the boundary layer. In order to do this, the differences between models need to be examined in a systematic way designed to reveal the effect of each operational parameter. Jones et al (1995) have made the best attempt at this, and both Bugg (1995) and Maul et al (1996) have made significant contributions. None have covered all the relevant modelling parameters and all have been limited in scope. All have been concerned with relatively early versions of the ADMS model and there have been no studies of this type since.

Only two recent studies, that of Hanna et al (1999a,b) and of McHugh et al (1999) compare the ADMS and AERMOD models against an older (ISC model), using field data. Only one other, brief and unpublished, study by Harvey (1998) looks directly at differences between the ADMS and AERMOD models. The other studies compare either the ADMS or AERMOD models with older models.

All the studies discussed here, from the work of Jones et al and of Bugg onwards, show that there are quite substantial differences between concentrations calculated by all the models of interest here. Maul et al showed that even the R91 and ISC models, nominally based on the same fundamental dispersion characteristics, showed differences in calculated concentration up to a factor of two. Both Bugg and Maul have also shown that nominally similar realisations of the same model can have substantial differences. They noted the importance of the choice of plume rise model (even of different realisations of, for example, the Briggs plume rise model) and its effect in markedly modifying concentrations at the ground.

The inter-comparison studies generally show some common conclusions. Differences between the newer ADMS and AERMOD models and the older R91 and ISC models are generally greater in stably and unstably stratified boundary layers than in neutral stability. ADMS and AERMOD tend to produce more rapid vertical dispersion in unstable flows, with the point of maximum ground level concentration moving more rapidly towards the source, and reduced vertical dispersion in stable flows, with the point of maximum ground level concentration moving further away from the source. This difference appears to be especially marked with the ADMS model, where several reports note the very rapid contact of airborne plumes with the ground in unstable flows. It appears that this feature of the ADMS model may have been modified through different versions. Hill et al's (1999) study indicated very little difference between ADMS and R91 model predictions of a set of field measurements mainly in neutral stability. However, Jones et al's earlier systematic studies showed their version of the ADMS model predicting steadily greater differences in ground level concentration from the R91 model as the atmospheric stability passed from unstable to stable, but with marked differences in the position of the maximum. Thus their predicted concentrations at the ground were closer in unstable than in neutral boundary layers. With the addition of plume buoyancy these differences tended to diminish. They and other authors have commented that, in some cases in stable flows, airborne plumes calculated with the ADMS model do not reach the ground in the near field. Studies using field data have shown that the AERMOD and ADMS models are overall a better fit to the data than the older R91 and ISC models. Plume rise calculations in all the models except ADMS seem to have converged on the Briggs model. The ADMS model uses a complex recursive procedure in which the plume rise is (as in principle it should be) dependent on the rate of dispersion. However, in the only direct comparison, by Carruthers et al, it appeared with one exception to give results little different from Briggs. In this exception the differences probably arose from differences in the calculated wind profile rather than in the plume rise calculation.

Only Hanna (1999a,b) and Harvey (1998) have directly examined differences between the ADMS and AERMOD models. Hanna found that overall the ADMS model was a better fit to the field data he used, but the difference was small within the order of accuracy of such comparisons. Harvey examined only a few calculations with annual hourly data (an important practical application) and found only limited differences between either the level or shape of annual average concentration contours.

However, there were much larger differences in both the distribution and level of shorter-term statistical parameters, for which there is a regulatory need. The use of annual hourly statistics in inter-comparisons seems quite rare, despite their regulatory importance.

A critical theme running though the different inter-comparison exercises is the importance of the way in which meteorological data is assessed and the attribution of parameters critical to dispersion, especially stability (Monin-Obukhov length scale), boundary layer height and surface roughness. This applies particularly to stability parameters and especially to the Pasquill/Gifford stability categories, where the attribution of the next higher or lower stability category alters calculated plume calculations, typically by a factor of 2.5-3. This is within the bounds of many of the differences found in the studies described here. The attribution of meteorological parameters is not a precise matter. For example, the same data fed into the AERMOD and ADMS model meteorological pre-processors will not yield the same boundary layer parameters for dispersion modelling. It is questionable to what degree differences between dispersion calculations in these models may be due to this cause; the matter has never been investigated. There is a good case for separating these two parts of a model in investigating its behaviour. In analysing field data there are additional complications as different methods of assessing boundary layer parameters commonly yield markedly different predictions. Carruthers et al remark on one example where ground based parameters indicated neutral stability while the boundary layer at higher levels appeared to be unstable. These problems are in part due to the boundary layer commonly being in a state of disequilibrium.

The reported investigations of building entrainment are by Jones et al (1995), Harvey and Obasaju (1999), Barrowcliffe and Harvey (1998) and one case by Hanna et al (1999a,b). All show major differences in calculated concentrations in the near field where building entrainment of the plume is important. In fact only the R91 model, the SCREEN version of ISC and ADMS have formal building entrainment models. The ISC and AERMOD models only calculate an enhanced dispersion starting at some distance from the building. This does not seem a very satisfactory state for an important practical dispersion problem. However, the USEPA PRIME model does attempt to account for building downwash more effectively (though it has not yet generated any inter-comparison studies). Jones et al's studies showed marked differences between the R91 and ADMS building entrainment models, with the ADMS model showing large fluctuations in concentration in the near field behind the building, as did Harvey and Obasaju (1999) and Barrowcliffe and Harvey (1998). It is possible under some circumstances, where there is partial entrainment of an elevated plume in a building wake, for there to be a perturbation in the downwind concentration distribution. However, that shown by these examples seems excessive. There have been some recent changes in the ADMS building entrainment model, but their effects on this behaviour are not known.

Comparative studies of the effects of topography seem to be limited to comparisons with field data, by Paine et al (1999) (who compared AERMOD and ISC) and by Hanna et al (1999a,b). There are no systematic studies of the effect of different types of topography on dispersion behaviour. Only the ADMS model calculates a modified topographic flow field and then the modified dispersion pattern over it. ISC uses a form of 'flagpole' receptor and AERMOD has an improved 'flagpole' type of calculation (Venkatram et al (1998)) which also accounts for the probability of a plume in a stable atmosphere passing over or around a hill. Hanna et al used the Lovett field data, against which AERMOD had been validated and against which it was by far the best performer.

The inter-comparison studies described here cover approximately the last six years, no significant earlier work having been found involving the ADMS model. The AERMOD model has been in its final release version (from Trinity Consultants) for only about 18 months, though available in various developmental formats earlier. Allowing for the repetition of presentation of the same work, there are essentially ten separate studies reported on here of the differences between the four models of interest, ISC, R91, ADMS and AERMOD. Of what might be considered the most substantial studies (those of Jones et al (1995), Carruthers et al (1996), Paine et al (1998), Peters et al (1999), Hanna et al (1999a,b) and McHugh et al (1999)), two were carried out by the developers of the AERMOD model and two (one partially) by the developers of the ADMS model. In one of the others it appears that a substantial proportion of the calculations were carried out by the developers of their respective models. Of the remaining inter-comparison reports, most are concerned with the use of different models in practical applications and directly reflect the problems that can arise from differences between model calculations. Only one of the reports on the ten studies (the shortform by Carruthers et al (1996)) has been subject to independent peer review and formal publication. About half are not formally open publications.

In the period since the first appearance of the ADMS model (around 1991/2) there have been no significant changes to the R91 or ISC models and the AERMOD model has been issued only recently in essentially a single final form, though there were some variant development versions. The ADMS model has been re-issued in approaching ten different versions during this time. Most of these are known to have involved changes to the model code but there have been no indications during this period as to how these changes might affect the resultant dispersion calculations. The only published study seems to be the recent work of Hall and Spanton (1999), who looked at differences between two different recent versions of ADMS (versions 2.2 and 3) in relation to the use of different meteorological data. This paper has not been subject to peer review either.

Considering the practical importance of differences between model calculations in a regulatory regime and the substantial changes in investment and operational practice that may hinge on them, the relatively casual way in which this has been treated in the UK appears surprising. There seem to have been no freely published, independent, disinterested studies of the differences between models or versions of models. The US EPA does not permit new versions of its models to be used until they have been subject to independent critical testing, the results of which are published (Schultze (1999)). The same attitude could usefully apply in the UK. There is a clear need for systematic examination of the behaviour of dispersion models and of the differences between them in an open and disinterested manner. The lack of this in the past has, in the authors' view, hampered a clear understanding of model behaviour, the effective development of improved models and their use in regulatory applications in an intelligent way.

This is perhaps more surprising of UK practice in view of the UK Royal Meteorological Society's Policy Statement on Atmospheric Dispersion Modelling (R Met Soc(1995)). This document discusses with some acumen 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 draws 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. Its appearance coincides quite closely with the start of the period covered by this review.

It is apparent from the work reported here that there is still much scope for the adoption of the guidelines and principles proposed in the policy statement.

# 4. ACKNOWLEDGEMENTS

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# APPENDIX A. Bibliography of ISC/ADMS/AERMOD/R91 Validation and Inter-comparison Papers

The papers are entered in author alphabetical order with the following annotations:

A A study involving AERMOD

I A study involving ISC, SCREEN or any other of the older EPA models.

D A study involving an ADMS model.

R A study involving the NRPB R91 model.

E A study involving small-scale experimental data, usually from wind tunnels.

F A study involving field experimental data.

B A study, not necessarily a direct inter-comparison, offering some insight into model behaviour useful for inter-comparison purposes.


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