EVALUATION OF NEW GENERATION ATMOSPHERIC DISPERSION MODELS

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ABSTRACT
The paper considers the regulatory view of evaluating dispersion models. In the UK, there is no proscription for regulatory studies and differences between dispersion calculations from different models and versions of models are then as important as their absolute veracity. An example shows variations in calculated concentration due to variations between two different versions of a model and two different sources of meteorological data. A simple standard test protocol that will reveal such differences is being developed as part of a model inter-comparison exercise between the USEPA ISC model, the USEPA AERMOD model and the UK ADMS model, which are the models most likely to be used for regulatory applications in the UK.

KEYWORDS ISC, AERMOD, ADMS, Test Protocol, Model Inter-Comparison, Regulatory Application, Dispersion Model.

INTRODUCTION
Dispersion models are used for many purposes, but one of the most important is as indicators 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. There are usually 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 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 due partly to the limited availability of meteorological data and partly 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, as is shown by the scale of these harmonisation conferences. 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 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 model, which is expected to be replaced by the newer, second generation 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 as most regulatory dispersion calculations in the UK had used either a single model 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 quite similar. Since then, the significantly more advanced, second generation 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. It has become the preferred model for major authorisation applications, so that use of a single model has still largely prevailed. However, the more recent appearance of the USEPA 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 two 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 accuracy. Such differences can directly affect regulatory decisions and it seems surprising, therefore, that relatively few inter-comparisons of this sort are published. A trawl through the papers of the last three harmonisation meetings reveals that the majority are 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.

A CASE STUDY

That such differences are not trivial is illustrated in the following example, which arose partly due to problems that occurred in a regulatory investigation which crossed the period of introduction of a new version of a model. At the same time, the possibility of using meteorological data from two different sources was under consideration. The differences between dispersion calculations using these options was therefore investigated. The details of the study are described in Hall and Spanton(1999). The two sources of meteorological data were the UK Meteorological Office and Trinity Consultants Inc, both of whom sell data for dispersion modelling in the UK. A typical comparison between the data sets of a years hourly data, for Finningley in South Yorkshire, UK, from the two sources is shown in Figure 1 for temperature, wind speed, wind direction and cloud cover, of which the last three especially directly affect dispersion calculations. They are not identical. A breakdown of the differences is shown in Tables 1 and 2, below, where it is clear that most of the data are the same within the digitisation limits of their measurement resolution and that their bulk statistics are quite similar. The differences are partly due to the wind speed and direction being averaged over the hour in the UK Meteorological Office data and over the first ten minutes of the hour in the Trinity Consultants data.

Parameter	**Resolution**	**Within Resolution**		**% of Total Within**	
		No of Hours	**% of Total**		
Temperature	±0.5°C	1572	18	99.6	±1°C
Wind Speed	±0.5m s^{-1}	3090	35	87	±1m s^{-1}
Wind Direction	±10°	3511	40	90	±20°
Cloud Cover	±1 Okta	7255	83	96	±2 Oktas

Table 1. Statistics of Meteorological Data Comparison. Data for Finningley, UK, 1994.

Statistic	Temperature °C		Wind Speed m s^{-1}	
	Met Office	Trinity	Met Office	Trinity
Annual Mean	9.95	9.95	4.33	4.48
Standard Deviation	5.71	5.71	2.59	2.72
Skewness	2.03	2.04	2.26	2.27
Kurtosis	3.49	3.49	4.35	4.38

Table 2. Statistics of Temperature and Wind Speed Between Meteorological Office and Trinity Consultants Data Sets. Data for Finningley, UK, 1994.

Figure 2 shows a detailed breakdown of the wind speed and direction data, for the two data sets for one year, 1995, and for one data set for one other year, 1993. It can be seen that the differences between the two single years are comparable to or greater than the differences between the two data sets for a single year. It can also be seen in Figure 2, that the Trinity Consultants data has, overall, the lower wind speeds of the two data sets in the lowest wind speed range and the higher wind speeds in the highest wind speed range. This results from the small additional variability in wind speed and direction due to the shorter averaging period for the Trinity Consultants data.

Figure 3 shows modelled concentration contour maps of annual average concentrations of the discharge from a power station stack of 200m height. These have been calculated, for a unit emission of 1kg s^{-1}, using the four combinations of the two meteorological data sets and two versions of the UKADMS model, versions 2.2 and 3.0, which were current during a transition period in the UK early this year. It can be seen that, though broadly similar, there were significant differences between the dispersion calculations, both in the positions and in the values (typically of the order of 20-30%) of the maximum concentration. Table 3, below shows the maximum values of the annual means (from Figure 3) and a number of higher percentile concentrations from the same calculations. They did not, in general, occur at the same sites.

Model/ Met data	Annual Mean	100 %ile	99.9 %ile	99 %ile	98 %ile	95 %ile
ADMS v2.2						
Met Office	0.53	291	49.5	20.4	7.07	1.01
Trinity	0.62	234	64	24.9	9.22	1.33
ADMS v3						
Met Office	0.50	64.6	46.6	19.3	8.97	0.80
Trinity	0.59	66.2	48.1	22.4	12.0	1.29

Table 3. Maximum Values of Annual Average and Hourly Averaged Higher Percentiles (in µg m^{-3}) Calculated Using the Four Combinations of Dispersion Model and Meteorological Data.
For a release of 1 kg s^{-1} from a 200m Stack.

Figure 4 shows a bar chart of the ratios of maximum concentrations for four combinations derived from Table 3. Some of the differences between different versions of the UKADMS model arise from changes in the meteorological pre-processor rather than the dispersion calculation itself. For example, Figure 5 shows the differences in boundary layer height calculated by the two model versions. About 9% of the values exceed a difference of $\pm$50m.

SATISFYING THE REGULATORY NEED – A PROTOCOL FOR MODEL INTER-COMPARISON

Though the scales of these differences in calculated concentrations might not be considered unusual in modelling circles, they are significant from a regulatory point of view. Here, the need is for a clear understanding of the differences in dispersion calculations that will arise in normal use due to variations in the use of different models, different versions of models and other sources of variation such as meteorological data or the choice of meteorological site.

The first stage in providing this information in the UK is the study presently underway for the UK Environment Agency, investigating the differences between the older ISC model and two of the second generation dispersion models most likely to be used in the UK for regulatory authorisation of industrial plant. These are the UKADMS model and the USEPA AERMOD model. The important feature of this study is that it is looking at differences between the models rather than their absolute veracity.

It is inevitable that such a study reduces in value as other models and newer versions of models appear. However, the regulatory need for this information remains and it has also been the intention of the study to develop a protocol for model testing that that can be used for future assessments by the Environment Agency. It is important to try and achieve this sort of continuity, so that new models, versions of models, and the effects of changes in other basic inputs such as meteorological data can be compared quickly and easily over long periods. The Agency is also considering whether it should propose that any new or modified regulatory models would not be accepted until such comparative data were available for its consideration.

In preparing such a protocol it is important to try and devise a test programme containing a relatively limited number of dispersion calculations, but which is sufficiently revealing 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(1991), Olesen(1995) and others in analysing model comparisons with experimental data, which is both numerous and scattered. However, this should not be necessary when comparing models (rather than comparing models with experimental data) which can be done in relatively simple systematic ways.

We initially identified those parts of dispersion model calculations that most affect regulatory practice, in order to devise a simple test procedure of limited size. The most important of these were considered to be (perhaps not surprisingly),

Basic rates of plume dispersion in neutral, stable and unstable atmospheres 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 topography on basic plume dispersion

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

The last item is the way in which regulatory calculations are normally done, so this type of comparison is important. However, the individual facets of the calculation cannot be readily deconvolved 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 separated from the fundamental model characteristics above. 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 left for separate consideration.

It is possible to devise a quite limited set of interlocking calculations, which will 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 shot calculations. The meteorological parameters, based on examples from site data, were fixed for these cases. The low wind speed case was used with three boundary layer depths to test large buoyant plume interaction with the top of the boundary layer.

Two stack heights, low (40m) and high (150m) with zero and high (5MW and 100MW respectively) buoyancy discharges.

Two building heights (attached to the lower stack) of 25m and 35m, of cubical and low, wide form. The relative heights of stack and building were designed to produce significant plume partitioning and wake entrainment in one case and significant plume down wash but no direct wake entrainment in the other.

The effects of topography were examined using a single, zero buoyancy 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 topography. It was felt that a real terrain presented a greater challenge to 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:

Three levels of gradient slope, normal, half and twice normal.

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

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

A total of about 75 single condition dispersion calculations were sufficient to cover the test cases and expose any essential differences between models. A further 18 calculations using a whole years 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.

DISCUSSION AND CONCLUSIONS

The paper has discussed the problems that arise in regulatory practice due to differences between dispersion model calculations. Considering the practical importance of this matter, it is surprising that it has received so little attention, particularly since such differences can be large. The example shown here, using two consecutive versions of a single model and meteorological data from two different sources, produced differences in the calculated concentrations that were significant from a regulatory point of view. There is a need for a simple, standard test protocol that will reveal such differences between models and versions of models over time. This has to be simple enough to allow differences to be revealed by straightforward comparison, but must also test all the critical features of a model. The test protocol laid out here is intended to do this and is being used in an inter-comparison exercise examining differences between the models most likely to be used for regulatory studies in the UK. These are the USEPA ISC model and the two second generation models, the UK ADMS model and the USEPA AERMOD model.

ACKNOWLEDGEMENTS

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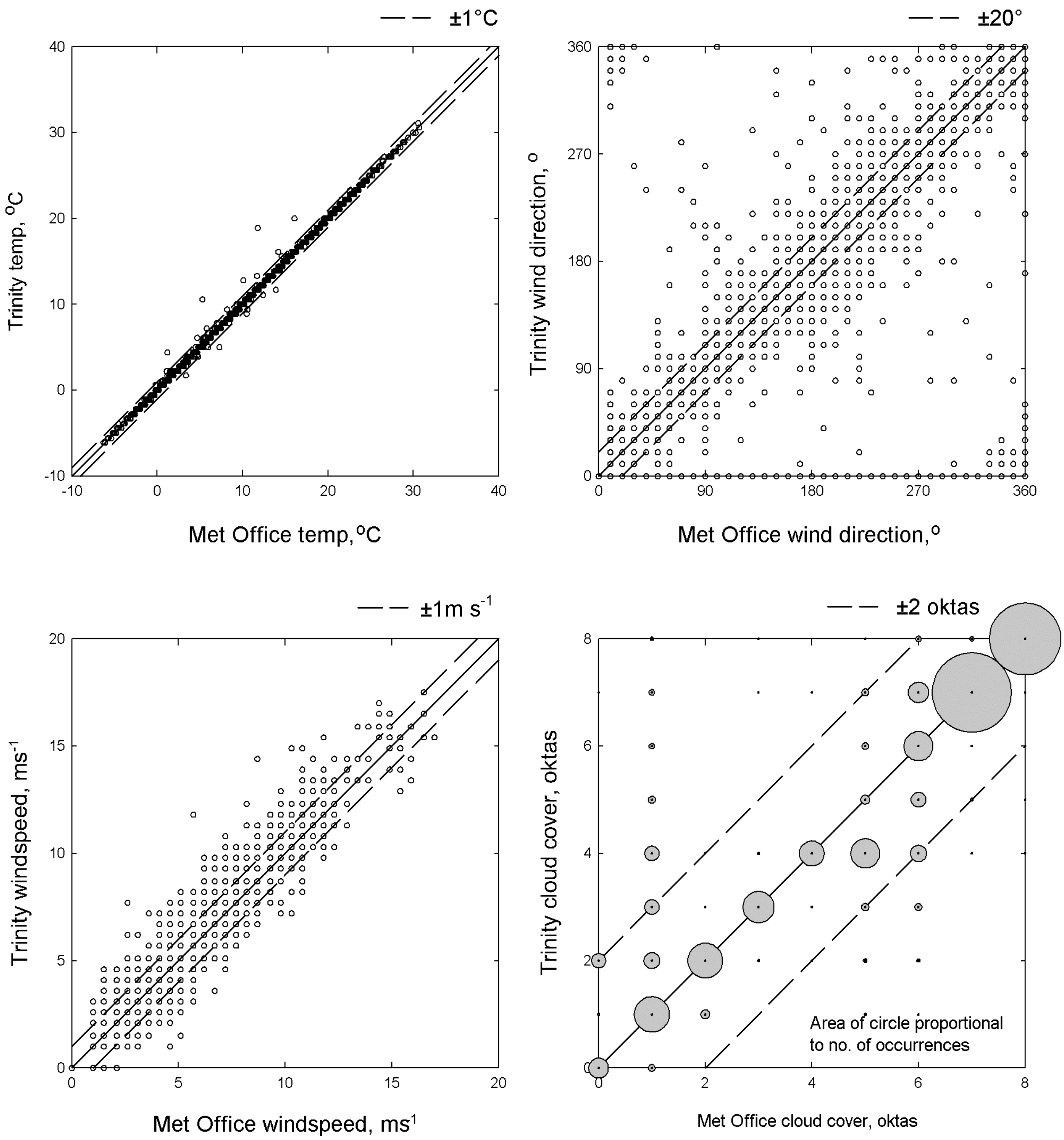


Figure 1. Comparative Plots of Wind Speed, Wind Direction, Temperature and Cloud Cover for Trinity Consultants and Meteorological Office Data. Data for Finningley, UK, 1994.

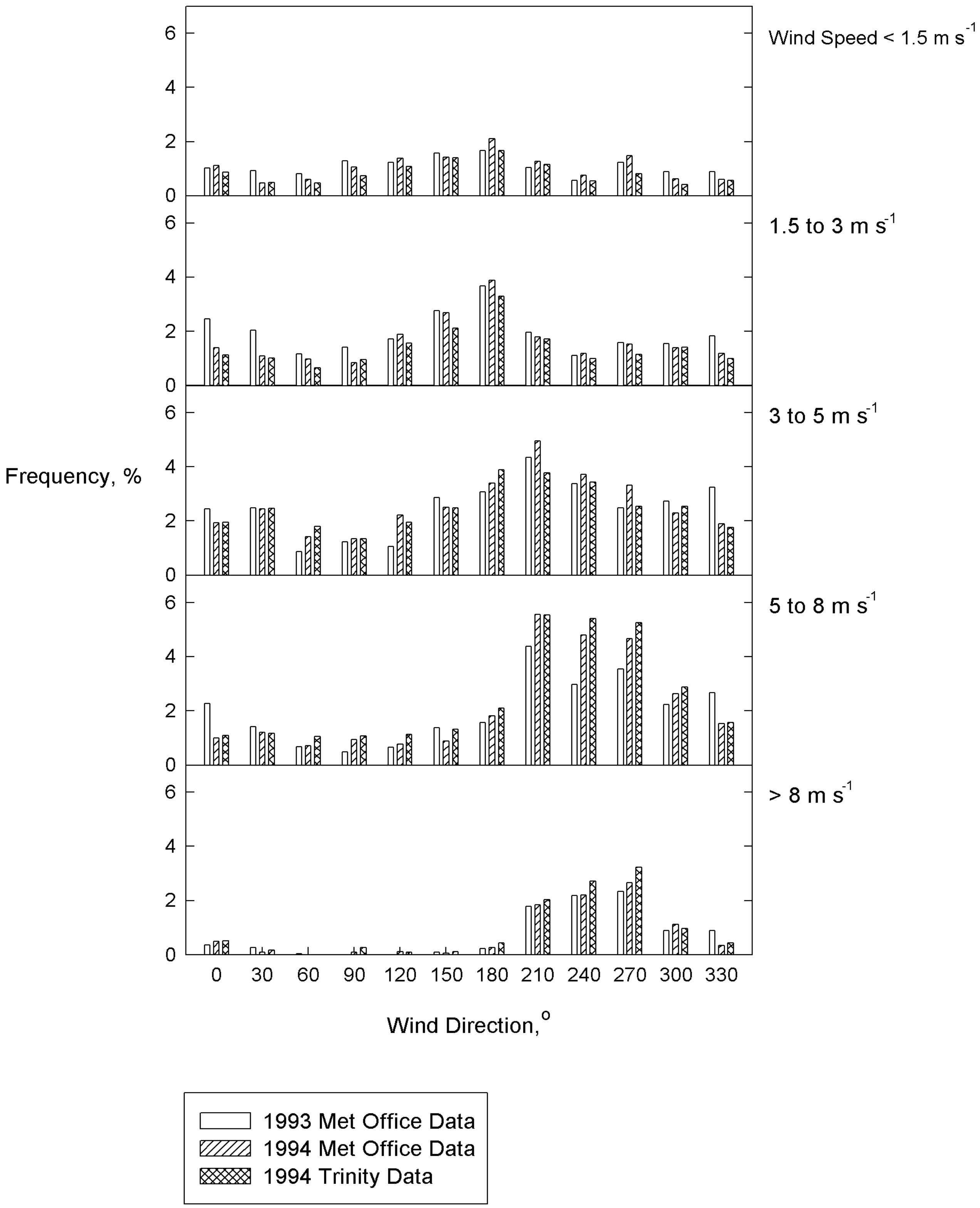


Figure 2. **Wind Speed and Direction Bar Charts of Trinity Consultants and Meteorological Office Data.**
Data for Finningley, UK, 1993 and 1994.

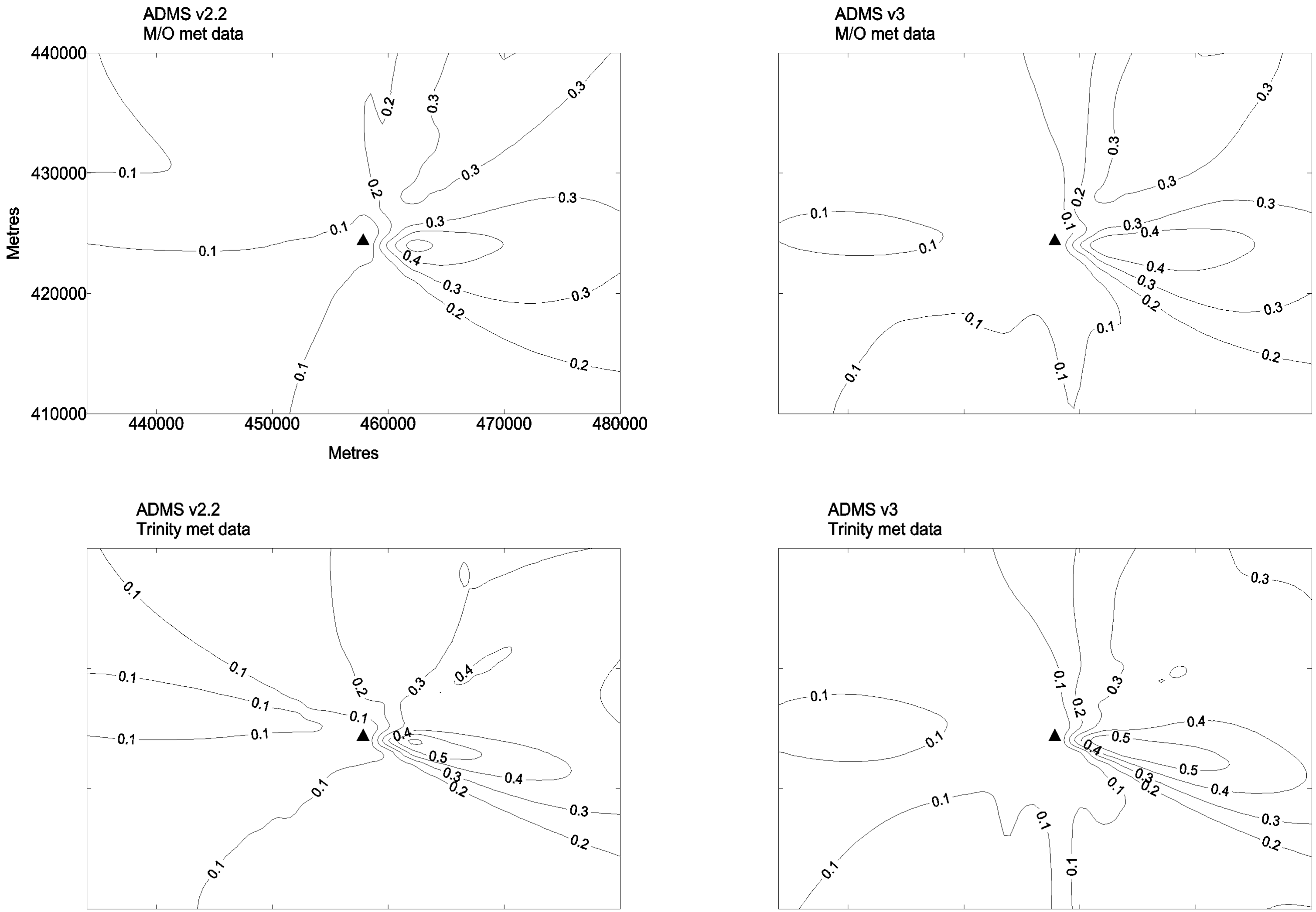
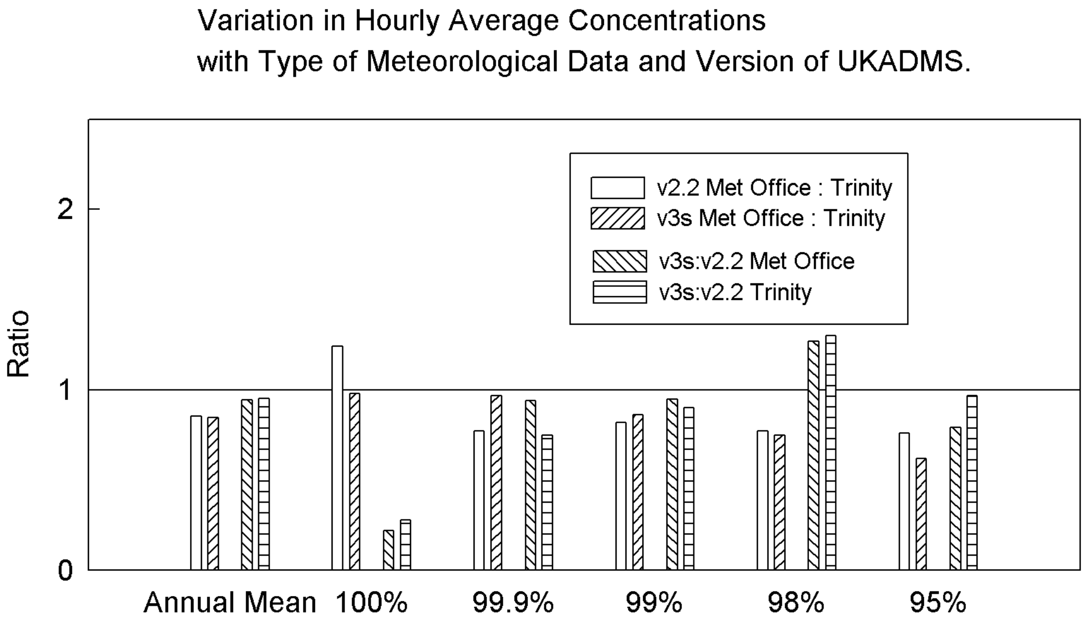


Figure 3. Contour Concentration Maps of Annual Concentration for the Two Meteorological Data Sets, Calculated using UKADMS Versions 2.2 and 3.
Concentrations in μg m^{-3} for an Emission of 1kg s^{-1}.



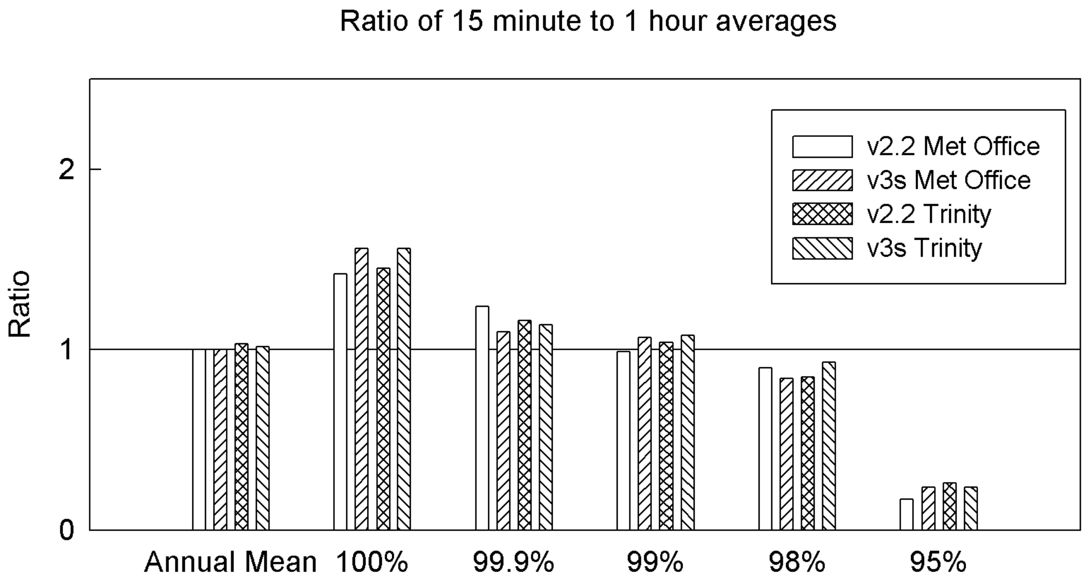


Figure 4. Bar Charts of the Concentration Ratios in Table 3 for Maximum Concentrations using Different Combinations of model and Meteorological Data.

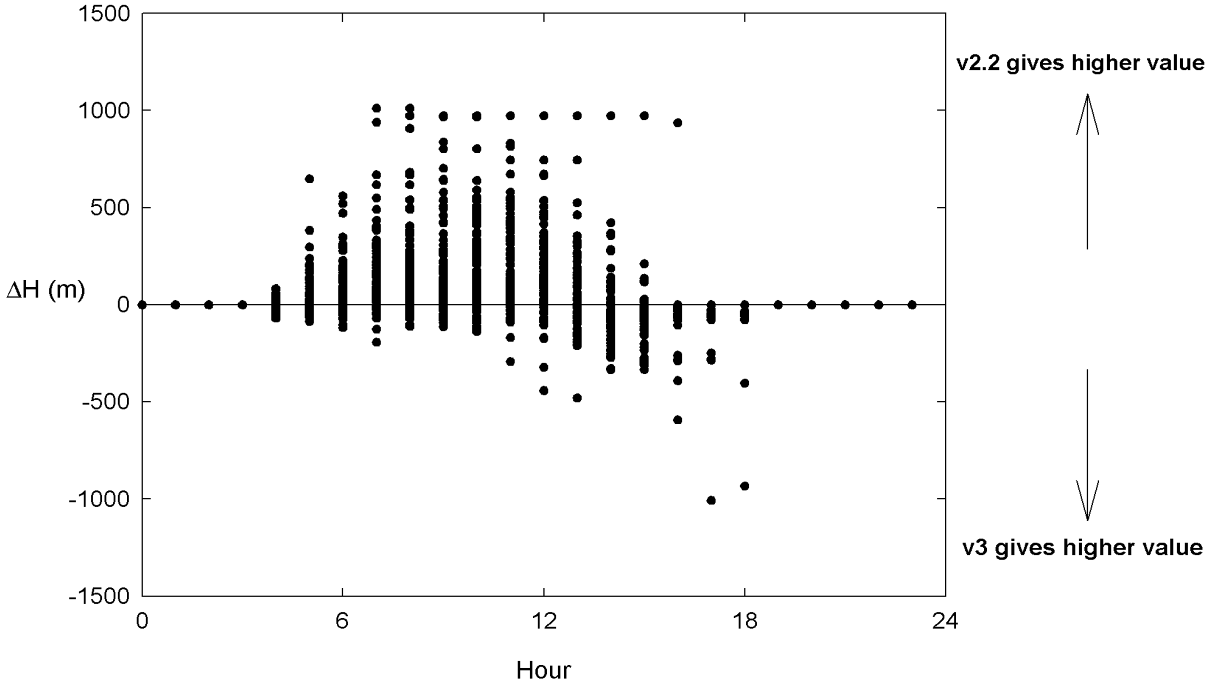


Figure 5. **Differences in Calculation of Boundary Layer Height Between UKADMS Versions 2.2 and 3.**
From Finningley, UK, 1994 Meteorological Office Data.