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A Sensitivity Study of the Validation of Three Regulatory Dispersion Models

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Abstract: Lidar measurements were made of the dispersion of the plume from a coastal industrial plant over three weeks between September 1996 and May 1998, 67 experimental runs were obtained, mostly of 30 min duration, and these were analysed to provide plume parameters (i.e. height, vertical and lateral spreads). These measurements were supplemented by local meteorological measurements at two portable meteorological stations and also by radiosonde measurements of wind, temperature and pressure profiles. The dispersion was modelled using three commercial regulatory models: ISC3 (EPA, Trinity Consultants and Lakes Environmental), UK-ADMS (CERC) and AERMOD (EPA, Lakes Environmental). Where possible, each model was run applying all choices as between urban or rural surface characteristics; wind speed measured at 10 m or 100 m; and surface corrected for topography or topography plus buildings. We have compared the range of output from each model with the Lidar measurements. In the main, the models underestimated dispersion in the near field and overestimated it beyond a few hundred m. ISC tended to show the smallest dispersion, while AERMOD gave the largest values for the lateral spread and ADMS gave the largest values of the vertical spread. Buoyant plume rise was modelled well in neutral conditions but rather erratically in unstable conditions. The models are quite sensitive to the reasonable input choices listed above: the full range of sensitivity is comparable to the difference between the median modelled value and the measured value.

Key words: Lidar, ISC, AERMOD, UK-ADMS, plume parameters, regulation, air quality

INTRODUCTION

Dispersion models are developed by scientists and engineers with the aim of using the best available technical knowledge to predict (typically) ground-level concentrations as accurately as possible. The models are then used by regulators in a quasi-judicial function to determine planning applications. If it were possible for atmospheric dispersion to be modelled both reliably and accurately, this process would be inherently fair. In practice, however, different models are inaccurate in different ways[1] and the regulator must be aware of such differences if he is to make equitable decisions.

In the present paper, we compare the predictions of three regulatory models with a substantial set of Lidar and meteorological measurements around a typical industrial plant. More broadly, however, we vary not merely the models but also the modelling procedures employed[2]. Models are typically validated in rather simple situations: single stack, flat terrain etc. They are then perforce employed in rather complex ones. This leaves the modeller considerable scope for choosing which complexities to include in his modelling, and which to neglect. We explore the consequences of such flexibility in this paper. The subject plant is on the margin between rural and urban terrain, with many significant buildings on site; it is on the coast; there is topography at slopes of up to 5%; and we have both surface and profile meteorological data available. All these issues may, or may not, be included in modelling intended to support an application for an authorization to operate.

The three models used in the study were ISC, AERMOD and UK-ADMS (3.1). The latter model was purchased from Cambridge Environmental Research Consultants (www.cerc.co.uk). The algorithms for ISC and AERMOD are available from the US Environmental Protection Agency (www.epa.gov), but we found it more convenient, initially, to use code provided by Trinity Consultants (www.trinityconsultants.com). The AERMOD code and meteorological pre-processor were

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subsequently purchased from Lakes Environmental (www.weblakes.com).

Field Work: Measurements were made around the Enichem plant on the SW shore of Southampton Water (Fig. 1) in the periods 9-13 September 1996, 12-15 May 1997 and 7-12 May 1998. This coastal site was chosen because it displays enough topographic complexity to challenge the models, while not having so much as to dominate the flow. Over the 600 m width of the site, the ground rises from 7.5 m above ordnance datum (AOD) near the shoreline to a height of 30-35 m. Further inland, the ground remains at around this height, though with substantial roughness elements: woods, housing and further industrial buildings. The site itself is covered with low-density buildings, mostly in the range of heights 10-30 m.

The emissions studied were released from a 72 m stack attached to a combustion plant. This burns a mixture of process gas, natural gas and heavy fuel oil in several units to raise steam for use in the manufacture of styrene. The internal diameter of the stack is 2.07 m and its base is at 24.5 m AOD. Under normal operating conditions, the emission velocity is 5.8 m s^{-1} at a temperature of 250^{o}C, implying a thermal emission of order 3.1 MW. The plant management supplied us with regular readings of the exhaust gas temperature, excess O_2, fuel consumption rate and the type of fuel used by each unit. These values were entered into a spreadsheet to calculate the aggregated volumetric flow-rate and emission temperature for each experimental run.

The various obstructions (trees and built structures) on site were surveyed using traditional methods: a 20' theodolite and 50 m measuring tape. Four observation points were selected, and distances and elevation angles of buildings measured from them, the overall arrangement being checked against an aerial photograph of the site. The mean area density of buildings on site (plan area/lot area) was found to be 31% with a mean building height (total building volume/plan area) of 14.5 m. The height above datum of the underlying ground surface was taken from the printed Ordnance Survey map.

The Lidar was that used in previous surveys [3,4]. It operated at 532 nm with a pulse repetition rate of 30 Hz. As configured for these measurements, it had a range (radial) resolution of 5 m. The beam would typically be scanned vertically using a steerable mirror with shots at 0.5^{o} separation. Thus, at a typical range of 300 m, the tangential resolution was 2.5 m. Typically, a scan would consist of 60 shots per scan and thus require 2 s. Several s delay were then required to prepare the system for the following scan. The system can be run continuously for several hours, obtaining around 550 scans per hour. The nominal ocular hazard distance for a single shot was 3.1 km, so there were breaks in scanning from time to time to allow for passing aircraft. In this study, runs were of 30 min duration wherever possible.

Depending upon the wind direction and the position of the Lidar, scans could be either approximately longitudinal to the plume or transverse. In the former case, values of plume height (h) and vertical spread (σ_z) could be obtained at a range of downwind distances[5]. In the latter, values of height, vertical and lateral spread (σ_y) can be obtained. Our usual practice, where possible, is to make transverse scans alternately at two distances downwind: this not only gives plume parameters at both distances but lag correlation techniques then permit estimation of the wind speed at plume height[6]. The wind direction, of course, can be estimated from the measured position of the plume relative to the stack. Overall, there were 67 successful runs in the course of the survey. Of these, 34 were analysed as transverse cross-sections and 41 as downwind cross-sections: on several occasions the plume lay at such an acute angle that, although the near-field scan could be treated as transverse, the far-field scan was effectively downwind (*cf.* Fig. 2).

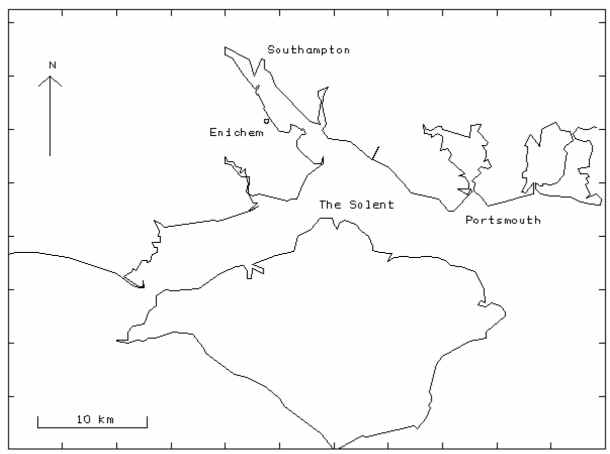

Fig.1a: General location of site on Southampton Water

For most measurements, the Lidar was situated 130-150 m from the stack on a bearing of SW to WSW. Given the obstructed nature of the site, however, the range of wind directions and distances which could be monitored from any location was somewhat restricted. The precise location was therefore changed from day to day in order to obtain an unobstructed view of the plume. On two occasions the plume direction obliged us to locate the Lidar outside the plant perimeter (sites C and G in Fig. 1c). The height of the usual location was 30 m AOD, implying that the beam-steering mirror, which determines the origin of coordinates of the scanning, was at 33 m

AOD. We should note that there is a major oil refinery and petrochemicals plant at 2-3 km and a power station (Fawley) at 5 km SE of the Enichem site: it was difficult to distinguish the Enichem plume reliably when the wind blew from this quarter.

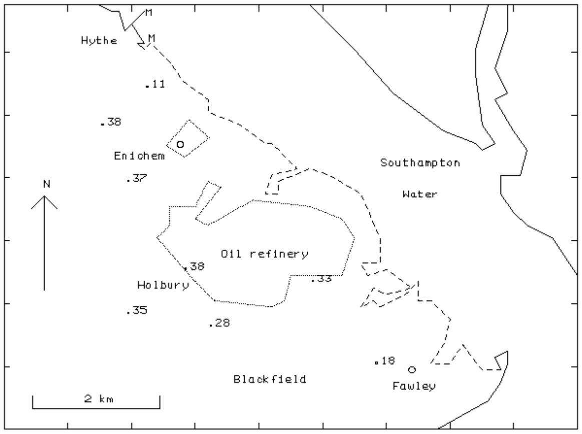

Fig. 1b: Survey area showing location of other pollutant sources and of meteorological stations (M). Spot heights give elevation in m above ordnance datum (AOD). The western shore of Southampton Water is mostly salt marsh, indicated by the dashed line.

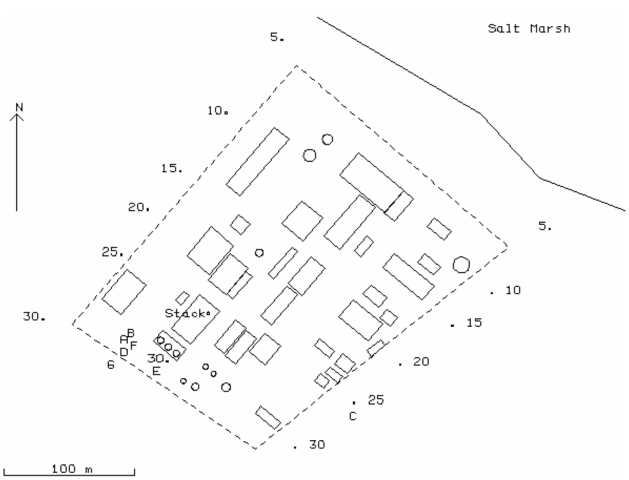

Fig 1c: Schematic layout of Enichem site, showing stack, Lidar locations (A-G) and spot heights in m AOD.

Meteorological data for the study came from two surface meteorological stations (MS) and from the regular release of radiosondes. Data were also available from local synoptic stations.

The Lidar vehicle has an attached MS consisting of a 10 m mast with a Porton wind vane and anemometer set (Vector Instruments model no.'s SRW1, A100). Temperature and humidity (Rotronic MP100) are also measured at this height. Short-wave radiation was measured with a pyranometer (Li-Cor, LI-200SZ) placed on the roof of the vehicle. All these variables were logged once every 10 s.

Since the Lidar MS was usually on the landward side of the plant, it was thought most appropriate for a second MS, again with a 10 m mast, to be sited on the foreshore: the sites shown in Fig. 1b were the closest available. For the first survey, an automatic weather station was hired from Vaisala[7]. For subsequent surveys it was deemed more cost-effective to buy a system, and that from Skye Instruments[8] was chosen. Unfortunately, the coastal site used for the first two surveys had been eroded into the intertidal zone by the time of the final survey. The local American marine base kindly granted permission for the MS to be located at the end of their jetty, 400 m further N.

It was recognized that the exposure of the surface MS's was rather poor and a series of radiosondes were released from the foreshore site to obtain boundary-layer data. In the first survey, a Loran-based system[9] was hired from the Meteorological Research Unit at Cardington. In this system, the position of the balloon, and hence the wind velocity, was determined by triangulation from a chain of UHF transmitters. As applied in our case, the Norwegian chain was used, with transmitters in Sylt, the Faeroes, Jan Mayen and the Lofoten Islands. The system (RS80-15L radiosondes from Vaisala) was specified to give a wind measurement with an accuracy normally better than 0.5 m s^{-1}. The height of the balloon was determined by the cumulative pressure and temperature profiles.

For the second and third surveys, the Cardington base unit was no longer available, but GPS technology had recently become available through Vaisala[10]. GPS sondes were therefore purchased for these two surveys and a GPS base station was hired from Southampton University. This system (RS80-18G radiosondes) is specified to give a wind measurement with an accuracy normally better than 0.2 m s^{-1}. We should note that wind measurement requires a measurement of differential position rather than the absolute position of the sonde: in civilian applications, this can be much more accurate. Where possible, radiosondes were timed to coincide with Lidar measurements, but it was often necessary to delay a launch slightly to enable the sonde to lock onto four satellites. (This number is needed to provide height as well as horizontal location). Over the course of the three surveys, 41 successful radiosonde ascents were made.

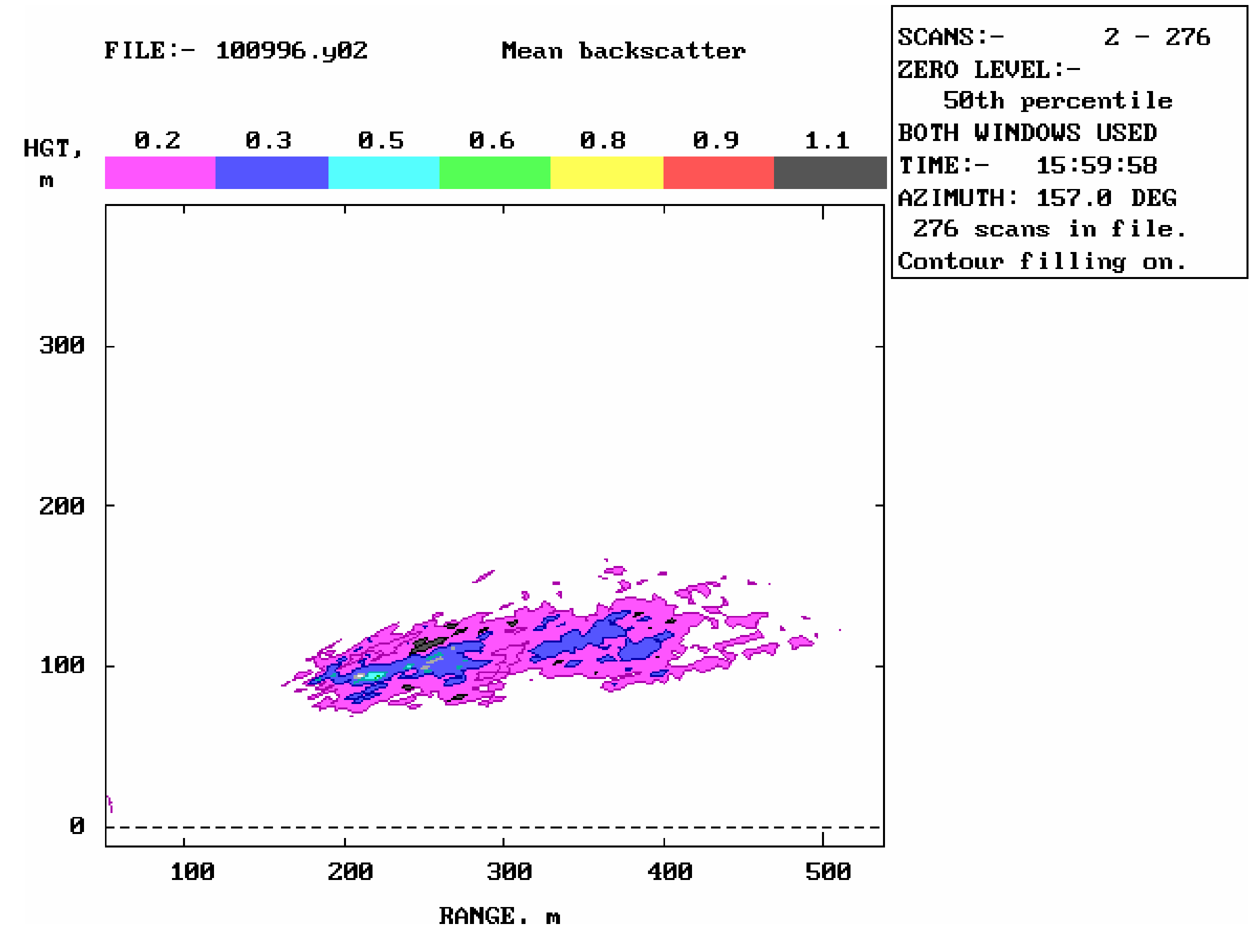

Fig. 2: A typical mean Lidar cross-section of the plume, averaged over 30 min. The scanning azimuth was 157.0^o; the calculated plume direction was 178.8^o with the centre-of-gravity of the cross-section being 344 m downwind. These measurements were analysed as a transverse scan.

Table 1: Meteorological variables measured with four systems. Note that the Lidar can only measure wind direction for transverse scans.

Determinand	Lidar-MS	Foreshore-MS	Radio-sonde	Lidar
Wind direction	*	*	*	*
Wind speed	*	*	*	*
Temperature	*	*	*	
Relaative humidity	*	*	*	
Dew point		*	*	
Shortwave radiation	*	*		
Pressure		*	*	

Table 1 summarizes the meteorological variables which were measured using the four systems.

Wind speed and direction data (sampling time 30 min) for the synoptic stations at Southampton and Lee-on-the-Solent were also purchased from the Meteorological Office. These stations lie respectively 10 km N and 10 km SE of the Enichem site (Fig. 1a).

DATA REDUCTION

The 67 Lidar runs were analysed to obtain the plume height and lateral and vertical spreads. Full details of the analysis procedure are given as an appendix in[11]. In essence, the Lidar signal is corrected for the inverse square dependence of backscatter with range and for the varying energy of each laser shot. A statistical technique is then used to identify the background signal from the atmosphere outside the plume; this becomes our effective zero level. There is no attempt to correct for the extinction of the signal with distance. (The standard procedure is given in[12]). Moments of the backscatter distribution in y and z are then calculated. After allowing for the geometry of the situation (position of source, position of Lidar, scanning azimuth) instantaneous values of h_i, σ_{yi}, and σ_{zi} could be calculated.

This procedure was carried out for each individual scan (duration 2 s). The models, however, predict dispersion over sampling periods of 30 min - 1 h. Thus, the Lidar data were averaged over their 30 min series. This presents no problems for first moment values such as the mean plume height, h (defined as the plume centre-of-gravity). For second moment values, however, i.e. the plume spreads, there are two possible time-mean values. In the case of vertical spread, for example, we have both the time mean of the values of σ_{zi} from the individual scans, but also the standard deviation, σ_h of the values of h_i for the individual scans: the plume loops as it spreads. For comparison with the regulatory models, we followed our previous practice[11] of adding these two in quadrature, i.e. $\sigma_z^2 = \sigma_h^2 + <\sigma_{zi}>^2$. It should be noted, however, that the instantaneous plume is significantly non-Gaussian, so if $<\sigma_{zi}>$ is a large fraction of σ_z, then the resultant time-averaged plume will not be Gaussian. Our Lidar estimates of plume spreads may thus not be strictly comparable to those in the models, where a Gaussian plume profile is usually assumed.

A substantial effort was applied to determining suitable boundary conditions for modelling the flow over the site, both for the surface roughness length, z_o and for the displacement height. Several methods were compared for the prescription of appropriate values of z_o. These included the application of a standard table of terrain types[13]; the use of a weighted sum over significant roughness elements[14]; a parameterization based on the mean plot density and height of obstacles[15]; and a parameterization based on the observed gustiness[16]. A very wide range (0.08 - 2.1 m) of possible values was obtained, depending upon the wind direction, the method employed, and the researcher responsible.

The heights and extent of the structures on the site were known from the theodolite survey. We then derived values for the ground elevation and the overlying structure heights on a 50 m grid over the site. A range of smoothing techniques (e.g. Kriging, radial basis functions) were applied to interpolate these heights to provide a continuous effective ground surface.

The most direct application of the topographic characterization of the site was in modelling the plume rise, since the height of the plume was measured relative to the Lidar, while the buoyant plume rise should be relative to the flowline at the height of emission. In order to correct for the deflection of that flowline relative to steady horizontal flow, one could make a range of assumptions of increasing complexity: (a) that the flow is uniform and horizontal, i.e. assuming flat terrain; (b) that the flowlines run parallel to the ground surface; (c) that the flowlines run parallel to the ground surface corrected for the built obstacles on the site; or (d) that a full 3D flow-field is calculated for the site. All of these assumptions were variously employed in interpreting our plume rise measurements and in comparing them with the model predictions.

In order to be able to model atmospheric dispersion from an elevated source, we need information on wind and turbulence profiles at the height of the release. Conventionally, models attempt to estimate such profiles from two classes of measurements:-

- *Surface measurements,* i.e. wind speed and direction at 10 m, surface heat flux, Bowen ratio etc.
- *Profile measurements,* i.e. radiosonde measurements of wind and temperature, Lidar measurements of aerosol.

In this study, we had surface measurements available from the Lidar MS for all times at which the Lidar itself was operating. These were averaged to give values of 10 m wind speed etc. over periods coincident with the Lidar runs. All the models used in this study accept such a surface wind speed as a model input and then attempt to extrapolate to the wind speed at plume height. In our study, however, we had also measured the wind speed at plume height using either the lag correlation technique applied to the Lidar measurements, or using the radiosonde measurements. Previous studies[11] have shown that this gives a superior prediction of plume rise.

UK-ADMS requires a relatively restricted set of input meteorological data. It can make use of whatever surface and profile measurements are available, employing boundary-layer theory to extrapolate dispersion parameters to an appropriate height[17]. Two sets of inputs are possible: as a bare minimum, wind speed and direction, cloud cover, time and date are required. The alternative option requires wind speed and direction and surface heat flux. If measurements of surface micrometeorology and of the boundary-layer depth are available, these can be used to improve the reliability of the modelling for either set of surface inputs.

AERMOD requires meteorological data in a more prescribed format for use by its meteorological pre-processor, AERMET, separate data files being required for surface meteorology and profile data. Our radiosonde and surface meteorological data were reformatted manually into the appropriate format, providing run-by-run files for use by AERMOD.

The modelling package we obtained from Lakes Environmental included both AERMOD and ISC. A similar process was required to collate meteorological files into the format required for ISC.

MODELLING

The aim of our study was to simulate the range of reasonable decisions that a modeller might make when attempting to model the dispersion of a plume in this complicated environment. To limit the number of permutations, we have restricted the modeller's possible choices to:-

- 'Rural' or 'urban' values for the surface roughness length (i.e. values of 0.03 or 1.0 m respectively).
- Wind speed measured at 10 m or plume height.
- Surface topography being treated as flat; true ground surface without obstructions; or true ground surface making allowance for buildings and other obstacles. This topography could be smoothed or unsmoothed.

Other meteorological variables (e.g. wind direction and the mixing height and Monin-Obukhov length derived from measured temperature profile) were held constant for each run.

Table 2: Surface parameters upwind of the stack as a function of wind direction.

Sector	Wind direction	Roughness length / m	Albedo	Bowen ratio
1	0^o – 130^0	0.0001	0.10	1
2	130^0 – 200^0	1.0	0.16	1
3	200^0 – 280^0	0.6	0.12	1
4	280^0 – 310^0	1.0	0.16	1
5	310^0 – 360^0	0.001	0.10	1

The values of roughness length quoted above were chosen as being typical values that an experienced modeller might have used. For consistency, we used the same parameters for all three models. In fact, AERMET permits a much more sophisticated treatment of the fetch upwind of the source, in that the roughness length, the albedo and the Bowen ratio can be allowed to vary as a function of wind direction. Values derived from the topographic survey are listed in Table 2. Note that for wind directions between N and SE, the upwind fetch is mostly over the sea, while from between SE and NW the fetch is over industrial plant.

Using these models, we simulated the transverse scans for the first two surveys and the longitudinal scans for the final survey. For AERMOD and ADMS, there were 12 possible modelling runs for each model and each experimental run. For ISC, however, the surface obstacles could not be included in the modelling, leaving only 8 model runs for each Lidar run. Overall, we made a total of 416 model runs for ISC and 672 for each of AERMOD and ADMS, making 1760 runs in all.

Although the measurements were typically made with a sampling period of 30 min, the shortest averaging time available for the AERMOD model was 1 h. For consistency, this averaging time was also used for ADMS and ISC. It may thus be expected that predicted plume spreads etc. will be somewhat larger than the measured values.

In the first instance, we wished to compare the model predictions of plume parameters with those measured by the Lidar. It should be recalled that the primary purpose of a model is to predict the concentration at some point, usually at the surface. The plume parameters used internally by a model are not therefore always accessible to the user. This was in practice the case with ISC. Instead, having run RAMNET to formalize the meteorological inputs, we used the published dispersion algorithms[18] to obtain σ_y and σ_z and a version of the Briggs plume rise equation to obtain the plume height, these being the algorithms which ISC uses. Full specifications may be found on the EPA website.

For AERMOD, Lakes Environmental kindly made available a β version of the software which output tabulated values of parameters for the direct plume. These could then be interpolated to obtain values of σ_y, σ_z and h at the downwind distances where the Lidar had measured them. We should note that the direct plume may differ significantly from the plume seen by the Lidar if this is interacting with the ground or with the top of the boundary layer. In practice, however, this was unlikely to be a problem at the relatively short downwind distances being studied.

There was no problem extracting values of plume parameters from the UK-ADMS runs. The model provides a graphical mode in which such parameters can be displayed as a function of downwind distance; the desired values can simply be read off.

As noted above, the primary purpose of a model is to predict concentrations. Unfortunately, given the restricted viewing conditions on site, it was not possible for the Lidar to follow the plume to the point where it reached the ground and hence to make direct comparisons between measured and modelled concentrations[4]. Even before the plume reaches the ground, however, some feel for how well the model is doing can be gained by taking the ratio of the ground-level concentrations predicted using the Gaussian equation, employing calculated or measured plume parameters, i.e.

$$\frac{C_c}{C_m} = \frac{\sigma_{ym}\,\sigma_{zm}}{\sigma_{yc}\,\sigma_{zc}} exp\{-\frac{1}{2}[(\frac{h_c}{\sigma_{zc}})^2 - (\frac{h_m}{\sigma_{zm}})^2]\}, \qquad (1)$$

where the subscript c denotes 'calculated' and m denotes 'measured'. This ratio was calculated for all the model runs. It should be stressed that the ratio does not predict the accuracy of the predicted ground-level concentration where the plume actually disperses to the ground: it is merely an indicator of the performance of the dispersion model at this intermediate point.

RESULTS

We have four parameters (σ_y, σ_z, h and C) and three models, which are to be compared with our Lidar measurements. The results are summarized in Figs. 3 - 6.

We may consider first the reliability of the plume rise modelling. This is displayed in Fig. 3. In all these Figs., we have plotted the ratios of the calculated, c, to the measured, m, values as a function of downwind distance. The simplest case is for the ISC model where the plume rise does not depend upon the surface roughness. We have plotted here only the predicted plume rise using the 10 m wind speed: we thus only have a single point per run per downwind distance. Transverse scans will provide plume parameters at two rather arbitrary distances per run; longitudinal scans will provide parameters at a range of distances at 50 m or 100 m intervals. Since we had extracted the plume rise module from ISC, there was no attempt to correct for the complexity of flow over the site. We thus corrected the measured height by assuming that the flow ran parallel to the smoothed surface-topography-plus-obstacles and compared this height with the modelled rise over flat terrain.

With the AERMOD and UK-ADMS comparisons, the converse technique was used. These models both attempt to simulate the flow over complex terrain. In the case of AERMOD, it is assumed that the flow runs parallel to the surface; in the case of UK-ADMS, the full 3D wind field is calculated using FLOWSTAR. Therefore, for these models we compare the measured geometric rise above the point of emission with the equivalent modelled values. Since each Lidar run is now shadowed by up to 12 modelling runs, each run now appears as a vertical bar, indicating the range of modelled values, in the Fig. .

It may immediately be seen that there are two separate components to the inaccuracy of the calculated values: the range of values predicted as a function of model inputs and the difference of these values from the measured plume rise. Regarding the latter, it should be noted that the plume rise at ranges of less than 100 m can be as little as 5-10 m. This approaches the precision of the Lidar measurement and is also within the range of correction for topographic effects. Precision is less of a problem at greater ranges. Figure 3 displays linear fits of the calculated ratios for all three models: as may be see they all imply acceptable agreement at the furthest range of 400 m. (Note that the linear regression lines appear curved on this logarithmic plot).

Of more interest, perhaps, are the broad spreads shown by the individual models according to the input choices made. These are typically at least as large as the differences between model and measurement.

Measured plume rise was also compared with the predictions of the simple Briggs plume rise formula[19]. In this case the rise is proportional to an empirical constant, C_1, for which Briggs, having reviewed the field studies then available, recommended a value of 1.6. This value was later supported by work[3], involving Lidar studies at several power stations; though it was noted that a value of only 1.3 might be appropriate at Fawley (Fig. 1b). (This was speculated to be a coastal effect). Assuming flat terrain, a very similar value (C_1 = 1.26±0.13 @ 95% CL) was derived from our present data, though the point-by-point correlation was rather poor ($r = 0.55$).

Disappointingly, the application of topographic corrections to the measured plume heights did not improve the agreement between the measured and modelled plume rise. As the measured height was corrected successively for surface topography, unsmoothed obstacles and smoothed obstacles, C_1 decreased to 1.12, 0.83 and 0.84 respectively. There was no significant change in the point-by-point correlation. The reduction in C_1 arises since the majority of the measurements were taken with onshore winds, i.e. the streamlines should have been rising and this rise subtracted from the measured plume height before comparison with the Briggs formula.

It should be noted that the values of C_1 were not arrived at by two-parameter linear regression, but simply by forcing the rise to be zero at the point of emission and taking the mean ratio of the predicted to measured rise. This takes no account of local streamline deflection around the boiler house or of the possibility of stack-tip downwash. (The wind speed at plume height often exceeded the nominal emission velocity of 5.8 m s^{-1}). Overall, a downwards streamline deflection of 11.5 m would have been sufficient to bring the final value of C_1 back up to 1.3. With a boiler-house height of 30 m, such a local deflection is feasible and it is not clear that it has been included in the treatment of the buildings as a smoothed addition to the topography.

Figs. 4 and 5 show the ranges of modelled/measured ratios for lateral and vertical plume spreads. In this case, the surface roughness makes a significant difference to the plume spreads modelled by ISC, so these values now appear as vertical bars rather than as single points. The initial impression is of considerable similarity between the modelled behaviours of σ_y and σ_z. We may note that AERMOD predicts the largest values of σ_y while UK-ADMS predicts the largest values of σ_z. ISC generally predicts the smallest spreads, except for σ_z in the near field.

All models apparently underestimate the spread at downwind distances of much less than 100 m but may increasingly overestimate it at distances of 400 m or greater. Again, some caution is appropriate at the smaller distances, since the measured standard deviations fall in the range 5-10 m. For such small spreads, there may be a significant contribution from the imprecision of the Lidar measurement. The apparent modelled/measured ratio is thus probably an underestimate.

The overestimation of plume spread at large travel times may be understood in terms of the behaviour of plume elements at travel times greater than the Lagrangian integral timescale, T_L. As noted in Section 3, the reported values of plume spread arise from adding in quadrature the instantaneous plume spread and the standard deviation of the plume's centre of gravity. Clearly, the first term must grow monotonically with distance (unless there is streamline convergence). The second term, however, need not. This is most clearly seen for σ_z. From a Lagrangian viewpoint, a puff emitted by the stack may initially be carried upwards or downwards according to the local velocity of the air into which it is emitted. Statistically, this then gives an initial averaged spread $\sigma_z \propto x$. Such updrafts or downdrafts cannot persist indefinitely and for times greater than T_L the classic Taylor analysis gives $\sigma_z \propto \sqrt{x}$. This general behaviour has been included in the various models. The Taylor analysis, however, is based on an exponential Lagrangian autocorrelation function[20] and takes no account of the flow being forced to return to the horizontal in the mean. If an updraft must be followed by a downdraft (and conversely), the correlation function will show a negative dip at travel times greater than T_L and σ_z will grow more slowly than with $\sqrt{x}$. It is even possible that time-averaged plumes might contract with distance[21]. Such contraction was noted for the Drax (Site R3) measurements in[11].

Similar considerations apply to σ_y. An analysis of tetroon measurements described in[21] demonstrated the existence of significant negative excursions in the autocorrelation function for travel times of greater than 10 min. The authors ascribed these to longitudinal vortices induced by a combination of wind and instability.

To an extent, the forced return to the mean may also be an artefact of the Lidar analysis: the ensemble mean wind direction has been defined *post hoc* by the direction of the centre-of-gravity of the mean plume. Thus if a puff has initially veered (backed) relative to the mean plume then at a travel time greater than T_L it is more likely than not to back (veer) towards the ultimate mean destination. Put differently, the models are intended to predict the full ensemble spread around the ensemble wind direction. As analysed, the Lidar does not measure this: it returns the relative spread around a particular realization. This may contribute to the modelled/measured ratios of the spreads being greater than unity in the far field, as seen in Figs. 4 and 5.

Finally, Fig. 6 gives an indication of the rate at which the modelled plume is approaching the ground, as indicated by the ratio defined in Equation (1). The range of ratios here has been plotted as a cumulative frequency plot for each model, the abscissa being scaled so that a log-normal distribution would give a straight line. The Gaussian term in Equation (1) leads to relatively small errors in the plume spread giving apparently huge values in the ratio. For example, if $h_m/\sigma_{zm} = 6$ and $h_c/\sigma_{zc} = 5$ (quite a modest discrepancy, and consistent with the parameter range of our measurements), the exponential term in Equation (1) would be $e^{-5.5} = 10^{-2.4}$. Peak ground-level concentrations would not be in error by anything like this amount, since wherever the peak occurs we must have $h \sim \sigma_z$. The ratio serves rather as a qualitative indication of how good the model will be in predicting the distance to the maximum: if the ratio is <1, it implies that the model will overestimate the distance necessary for the plume to disperse to the ground. From the numbers just given, we seen that as long as the ratio is within $10^{\pm 2.4}$, then the distance of the maximum is likely to be correct to about 25%. We see that ISC-Urban is reasonably robust from this point of view, with slightly more than 50% of values falling within this range. ISC seems to underestimate the vertical rate of spread of the plume, while UK-ADMS seems to overestimate it. Including the surface topography in the UK-ADMS calculation decreases the modelled plume height and therefore increases the estimated surface concentration. These values should all be treated with caution, however, since in the near field both h_m and σ_{zm} will be affected by the imprecision of the Lidar measurement.

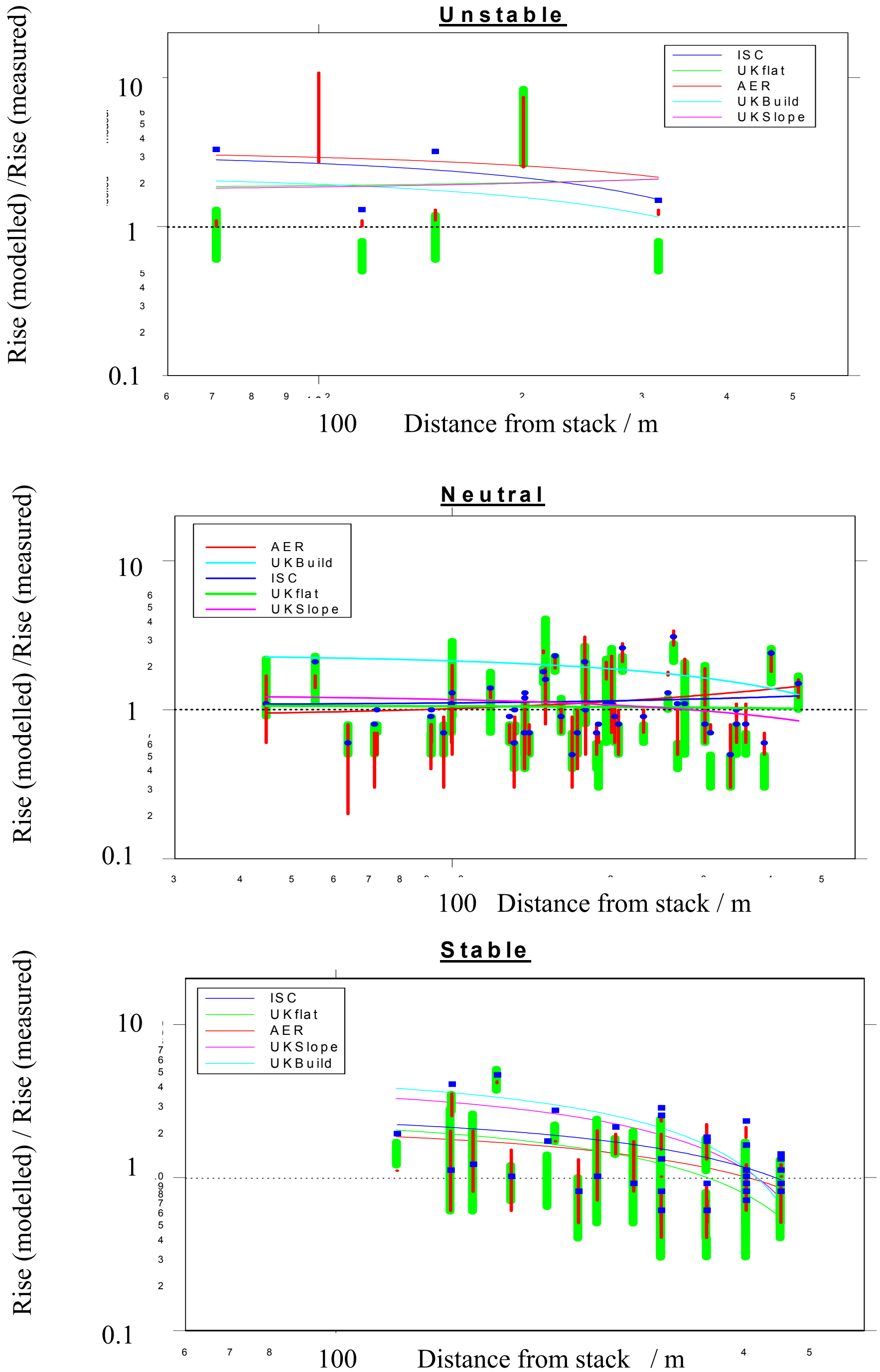

Fig. 3: Ratio of modelled to measured plume rise over flat terrain as a function of distance downwind for unstable, neutral and stable stability categories: UK = UK-ADMS; AER = Aermod; Flat = Assuming flat terrain; Slope = Including topography; Build = Including also buildings.

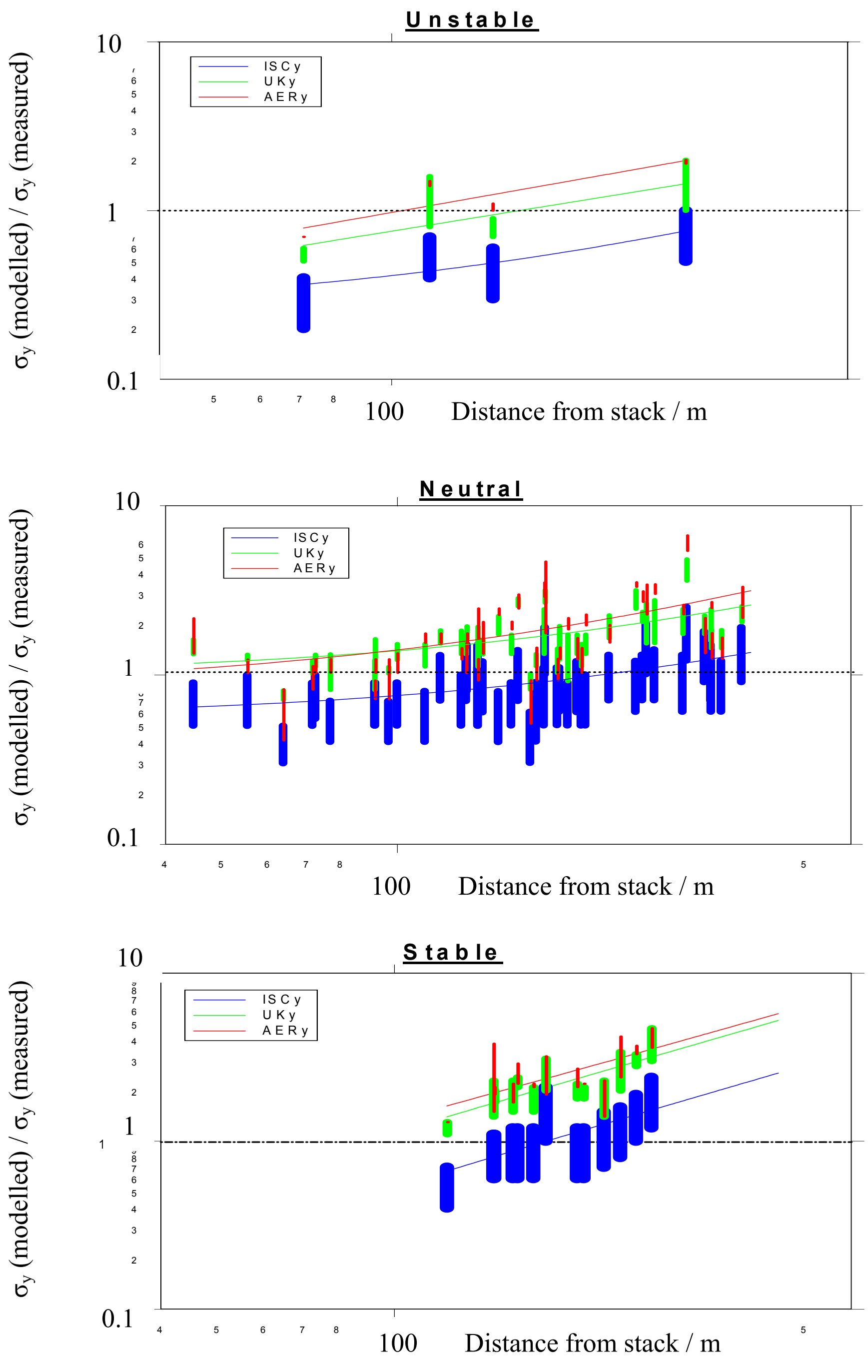

Fig. 4: Ratio of modelled to measured lateral plume spread as a function of distance downwind for unstable, neutral and stable stability categories.

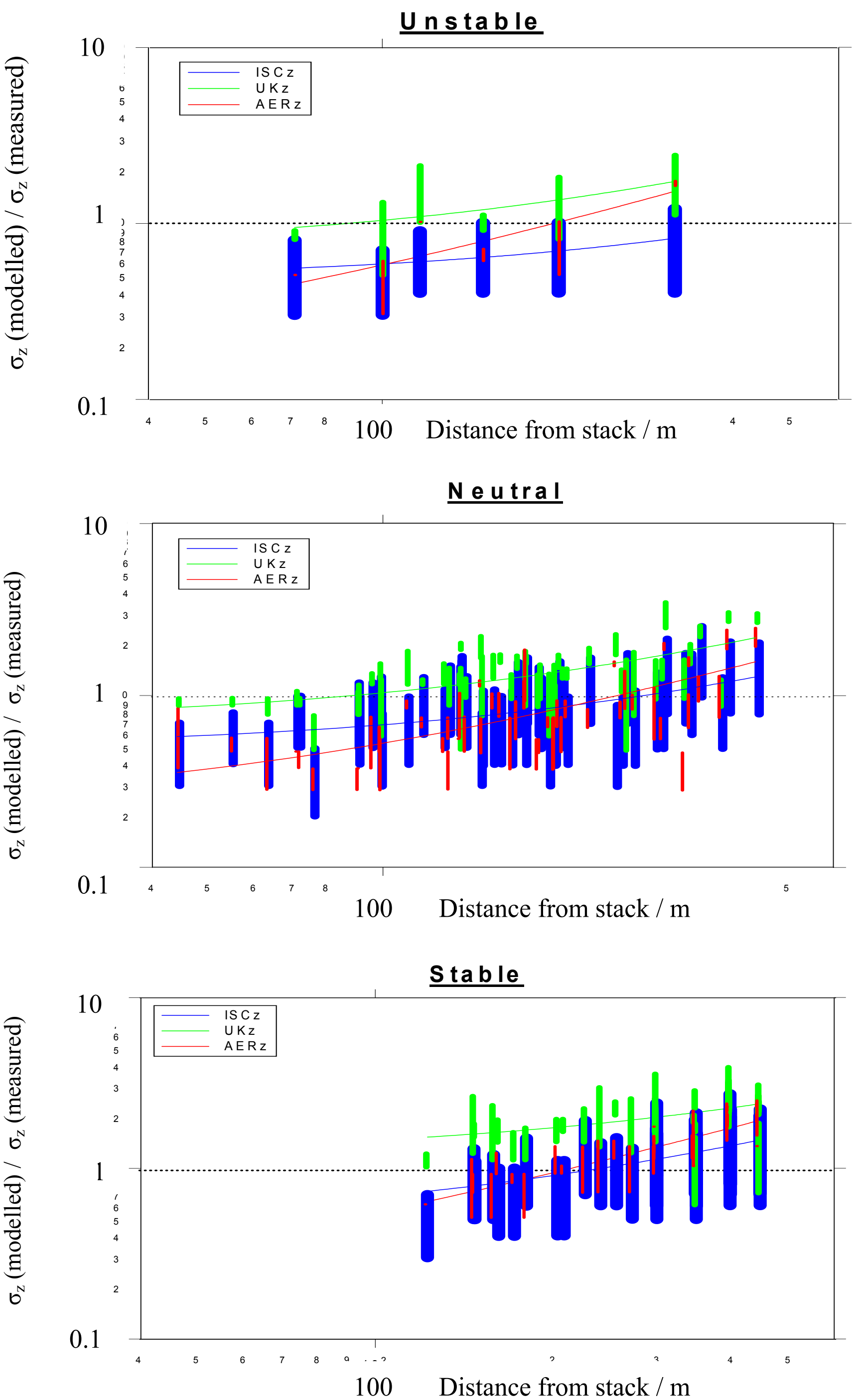

Fig. 5: Ratio of modelled to measured vertical plume spread as a function of distance downwind for unstable, neutral and stable stability categories.

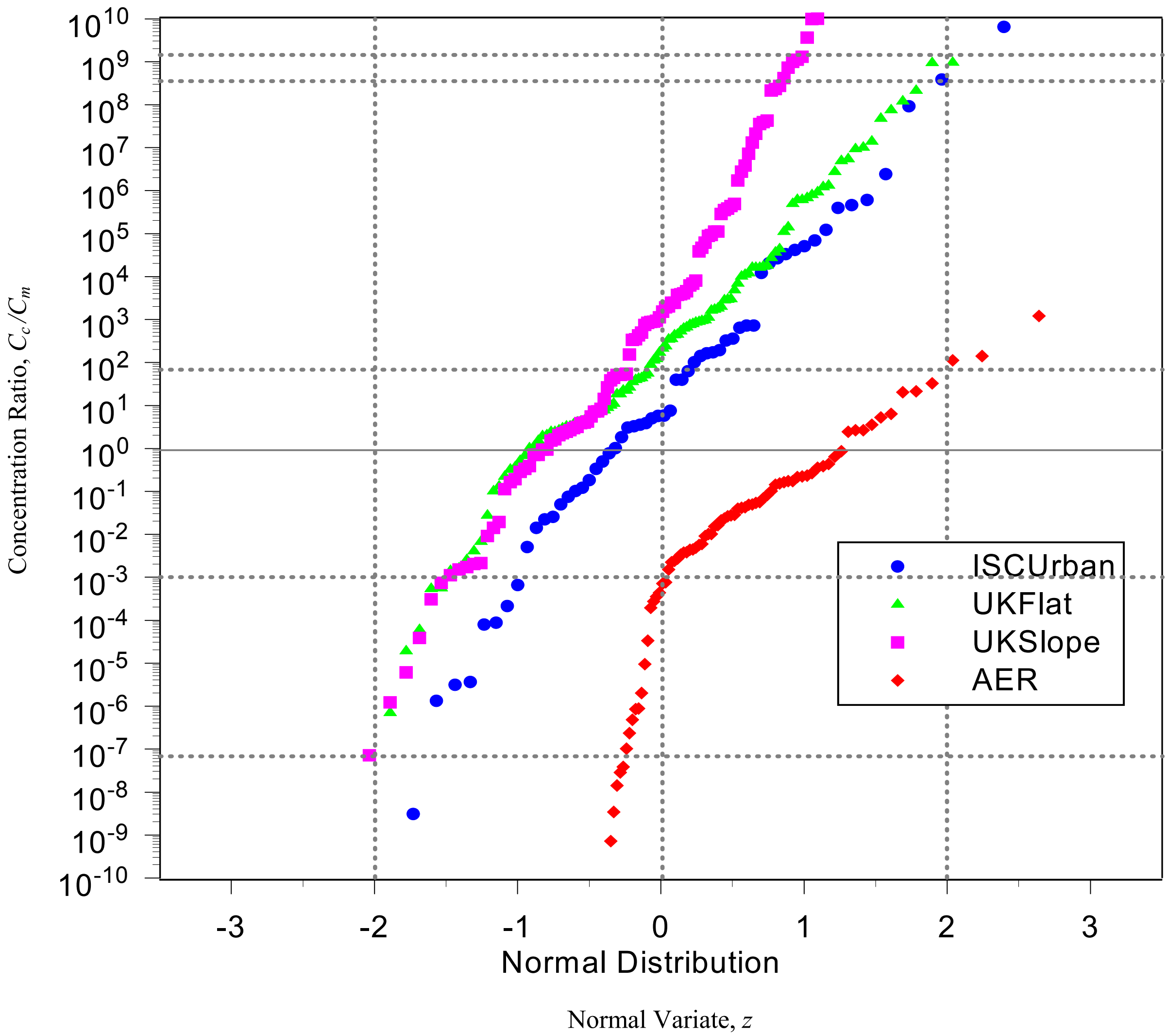

Fig. 6: Cumulative frequency distributions of the ratio of modelled (**c**) to measured (**m**) ground-level concentration for all runs. The abscissa has been scaled so that a lognormal distribution would give a straight line.

DISCUSSION

The core results of this paper have been presented in Figs. 3-5. We have seen that the agreement between modelled and measured parameters is reasonable, given the imprecisions in the measurements and the nature of the models. Of greater concern should be the rather broad spread in predicted parameters resulting from the range of reasonable choices which the modeller might have made in applying these models. A modeller should, of course, be able to justify both his choice of modelling procedure and his selection of input data[2]. Where possible, the meteorological input data should be local to the modelled site. In practice, however, qualitative justification will always be possible over quite a broad range of possible inputs. Moreover, it is not clear from the sensitivity study carried out here that the most sophisticated inputs necessarily lead to the most accurate predictions.

Traditionally, the regulatory authorities in the UK have been much less prescriptive than those in the USA as regards the choice of dispersion model. A model need merely be 'fit for purpose'. We see, however, that even prescribing the model will not be sufficient to prescribe the outcome. Where the authorization of significant capital plant is in question, this seems inequitable. If the regulator is to be fair as between one applicant and another, it seems he could follow two strategies:

1. Prescribe in detail the model, the modelling procedures and the input data to be used in various situations
2. Require a quantitative rather than a qualitative justification of the modeller's approach. The applicant should thus present not merely a model calculation but also a sensitivity analysis of that calculation.

The first strategy leaves the applicant with as little margin as possible to direct the modelling towards a favourable outcome. This is undesirable from a purely technical point of view, since it gives no opportunity for a skilled modeller to optimize the predictions for a particular site. It also serves as a brake on technical innovation, and would require a substantial investment by the regulator in developing a watertight protocol.

The second strategy is technically preferable but implies significant recurrent costs both for the applicant (in performing the sensitivity analysis) and the regulator (in appraising it). It also fails to achieve closure: the applicant and regulator might now argue about the sensitivity study rather than about the model on which it was based.

As a final comment, we may regret that in this complex environment, it was not possible to follow the material to ground level with the Lidar; both for reasons of simple obscuration and for eye safety. In practice, such studies can only normally be carried out for a single stack in flat terrain (e.g. [4]). Inconveniently, the installation we studied here is much more typical of the usual industrial situation: moderate topography, coastal site, complicated buildings and interferant emissions from nearby plants.

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REFERENCES

1. Hall, D.J., A.M. Spanton, M. Bennett, F. Dunkerley, R.F. Griffiths, B.E.A. Fisher and R.J. Timmis, 2002. Evaluation of new generation atmospheric dispersion models. International Journal of.Environment and Pollution, 18: 22-32.
2. Royal Meteorological Society, 1995. Policy Statement: Atmospheric dispersion modelling: guidelines on the justification of choice and use of models and the communication and reporting of results. Royal Meteorological Society, 104 Oxford Road, Reading RG1 7LJ. UK.
3. Bennett, M., S. Sutton and D.R.C. Gardiner, 1992. An analysis of Lidar measurements of buoyant plume rise and dispersion at five power stations. Atmospheric Environment, 26A: 3249-3263.
4. Bennett, M. and G.C. Hunter, 1997. Some comparisons of Lidar estimates of peak ground-level concentrations with the predictions of UK-ADMS. Atmospheric Environment, 31: 429-439.
5. Bennett, M., 1995. A Lidar study of the limits to plume rise in a well-mixed boundary layer. Atmospheric Environment, 29: 2275-2288.
6. Sutton, S. and M. Bennett, 1994. Measurement of wind speed using a rapid-scanning Lidar. International Journal of Remote Sensing, 15: 375-380.
7. Vaisala, 1994. Solutions to surface weather observations. Vaisala (UK) Ltd., Suffolk House, Fordham Road, Newmarket, Suffolk CB8 7AA, UK.
8. Skye Instruments, 1996. Instrument catalogue. Skye Instruments Ltd., Unit 21, Ddole Enterprise Park, Llandrindrod Wells, Powys LD1 6DF, UK.
9. Vaisala, 1989. Loran fundamentals (Micrologic). Vaisala (UK) Ltd., Suffolk House, Fordham Road, Newmarket, Suffolk CB8 7AA, UK.
10. Vaisala, 1995. GPS wind finding. Vaisala (UK) Ltd., Suffolk House, Fordham Road, Newmarket, Suffolk CB8 7AA, UK.
11. David. J. Carruthers, H. Edmunds, M. Bennett, P.T. Woods, M.J.T. Milton, R. Robinson, B.Y. Underwood and C.J. Franklin, 1996. Validation of the UK-ADMS dispersion model and assessment of its performance relative to R-91 and ISC using archived Lidar data. UK Department of the Environment, Research Report no. DOE/HMIP/RR/95/022.

12. Klett, J.D., 1981. Stable analytical inversion solution for processing lidar returns. Applied Optics, 20: 211-220.
13. Roland B. Stull, 1988. An introduction to boundary layer meteorology. Kluwer Academic Publishers, Dordrecht.
14. Kondo, J. and H. Yamazawa, 1986. Aerodynamic roughness over an inhomogeneous ground surface. Boundary-layer Meteor., 35: 331-348.
15. Macdonald, R.W., R.F.Griffiths and D.J.Hall, 1998. An improved method for the estimation of surface roughness of obstacle arrays. Atmospheric Environment, 32: 1857-1864.
16. Wieringa, J., 1986. Roughness-dependent geographical interpolation of surface wind speed averages. Quarterly Journal of the Royal Meteorological Society, 112: 867-889.
17. CERC, 1999. ADMS technical specification (V.3). Cambridge Environmental Research Consultants, 3d King's Parade, Cambridge CB2 1SJ, UK.
18. Griffiths, R.F., 1994. Errors in the use of Briggs parameterisation for atmospheric dispersion coefficients. Atmospheric Environment, 28: 2861-2865.
19. Briggs, G.A., 1975. Plume rise predictions. In: Lectures on Air Pollution and Environmental Impact Analyses. pp. 59-111. American Meteorological Society, Boston, MA.
20. Tennekes, H., 1979. The exponential Lagrangian correlation function and turbulent diffusion in the inertial subrange. Atmospheric Environment, 13, 1565-1567.
21. Phillips, P. and H.A.Panoksky, 1982. A re-examination of lateral dispersion from continuous sources. Atmospheric Environment, 16, 1851-1859.
22. Keith D. Harsham, 2002. Dispersion of industrial plumes in a coastal environment. PhD Thesis, Dept. of Chemical Engineering, UMIST, Manchester, UK.