VALIDATION OF A LAGRANGIAN MODEL PLUME RISE SCHEME AGAINST THE KINCAID DATA SET

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INTRODUCTION

Emissions from power station stacks and many other anthropogenic sources have substantial vertical velocities and are often hot compared with the surrounding ambient air. These momentum and buoyancy effects cause the emitted plume to rise, increasing the effective source height and, in the main, reducing maximum ground level concentrations. It follows that an accurate prediction of plume rise within atmospheric dispersion models is important, particularly at distances near to source and at times when the boundary layer is shallow enough to enable the effluent to penetrate the boundary layer top into the stable layer aloft.

In this paper a new plume rise scheme for the Lagrangian model NAME is described. We use the Kincaid data set to validate the scheme and compare the model with other leading atmospheric dispersion models at short range.

THE PLUME RISE SCHEME

NAME is a Lagrangian model in which large numbers of particles are released into the model atmosphere (*Maryon, R.H. et al.*, 1999). Each particle represents a certain mass of the pollutant which is depleted over time, if appropriate, by wet and dry deposition processes, radioactive decay or chemical transformations. The particles are advected by three dimensional ambient winds obtained from the Met Office's numerical weather prediction model, the Unified Model. Dispersion due to atmospheric turbulence is simulated using random walk techniques. The plume rise scheme models the rise of the plume due to momentum and buoyancy effects until the plume becomes neutrally buoyant.

The original plume rise scheme within NAME used the well known formulae given by Briggs and others (see *Briggs, G.A.*, 1984 and *Weil, J.C.*, 1988 for details). These formulae have been shown to agree with both observational and wind tunnel data. A new plume rise scheme has been developed for NAME which solves an integral model based upon the governing conservation equations of mass, momentum and heat as used in the Atmospheric Dispersion Modelling System (ADMS) (*Robins, A.G. et al.*, 1999). These conservation equations are consistent, under certain assumptions, with the analytical formulae given by Briggs and others and, in addition, should be suitable for a wider range of meteorological conditions.

The integral model is solved following each particle separately using local mean flow properties at the particle position. As a result the effect of the detailed wind and temperature profiles obtained from the Unified Model, including the temperature inversion at the top of the boundary layer, are taken into account. Mixing of ambient air into the plume is modelled throughout the plume rise process using the concept of an entrainment velocity.

In addition to altering the mean height of the plume, plume rise generates turbulence which will increase the plume size. This plume rise generated turbulence is greatest in the initial stages and is included within our scheme by adding a random displacement with prescribed mean and variance to each particle at every time step. The plume rise scheme is terminated when the plume becomes passive (i.e. the magnitude of the vertical velocity of the particle relative to the ambient flow falls below some nominal small value) or after one hour, whichever is sooner.

MODEL ASSESSMENT

The Kincaid field experiment was an extensive experimental campaign in which a buoyant plume containing SF_6 was released from the Kincaid power plant (*Bowne, N.E. and R.J. Londergan*, 1983; *Hanna, S.R. and R.J. Paine*, 1989). Ground level concentrations were measured along arcs at fixed distances between 0.5km and 50km from the source. The arc-wise maxima were recorded and can be used to assess the ability of a model to predict maximum ground level concentrations in mainly convective conditions at short range. A quality indicator has been assigned to the observed concentrations to indicate the reliability of the measurement in representing the true arc-wise maxima. During the measurement period, meteorological data was obtained from a 100m observation tower at the power plant site. Observed concentrations and meteorological data are distributed as part of the Model Validation Kit (*Olesen, H.R.*, 1994).

NAME is designed to run using output from the Met Office's numerical weather prediction model, the Unified Model, as meteorological input. Unfortunately, Unified Model output for the experimental period is unavailable and consequently some pre-processing is required to extend the hourly single site meteorological data provided with the Model Validation Kit into three dimensional fields acceptable by NAME.

The mean and standard deviation (σ) of both observations and model predictions are calculated. Performance measures obtained as part of the model assessment procedure are the bias, normalised mean square error (NMSE), correlation (r), fractional bias (FB), fractional bias in the standard deviation (FS) and proportion of values within a factor of two (FA2) of the observed maximum concentrations (*Hanna, S.R. et al.*, 1991).

RESULTS

Statistics for data of quality 3 (i.e. the most reliable data) are presented in Table 1.

Table 1. Performance statistics obtained using Kincaid data of quality 3

	Mean $\mu g\ m^{-3}$	σ $\mu g\ m^{-3}$	Bias $\mu g\ m^{-3}$	NMSE	**r**	**FB**	**FS**	**FA2**
Observations	0.692	0.513	0.0	0.0	1.0	0.0	0.0	1.0
Old plume rise	1.19	1.05	-0.501	1.51	0.341	-0.531	-0.687	0.616
New plume rise	0.578	0.575	0.114	1.07	0.306	0.180	-0.113	0.667

Table 1 clearly shows that the new (conservation equation) plume rise scheme outperforms the original (Briggs formula) scheme for data of quality 3. The new scheme slightly under-predicts maximum concentrations (positive bias) but gives good agreement with the observed mean and standard deviation. The old scheme over-predicts substantially (negative bias) and exhibits too much variation (σ). The new scheme also shows significantly better performance in the normalised mean square error, fractional bias and fractional standard deviation statistics. The fraction of values within a factor of two of observations reaches a highly respectable 67% for the new scheme. Correlation is the only statistic for which the new scheme is outperformed, reaching an unimpressive value of just 0.3.

The ratio of the predicted concentrations to the observed concentrations, *C MOD/C OBS*, is known as a residual. The behaviour of the residuals for data of quality 3 is displayed in Figures 1 and 2 using a box format. Data has been grouped according to a number of physical and meteorological variables namely distance from source, wind strength, stability (as characterised by z_i/L, where z_i is the boundary layer depth and L is the Monin-Obukhov length) and boundary layer depth. The cumulative distribution function of the residuals within each group is denoted by the 5th, 25th, 50th, 75th and 95th percentiles. For a good model, the residual boxes should be small and should not deviate too much from unity. Furthermore, the residuals should not demonstrate any dependence on variables such as downwind distance, stability and wind speed. The dashed horizontal lines in Figures 1 and 2 define the boundaries of the area within which modelled values lie within a factor of two of observations.

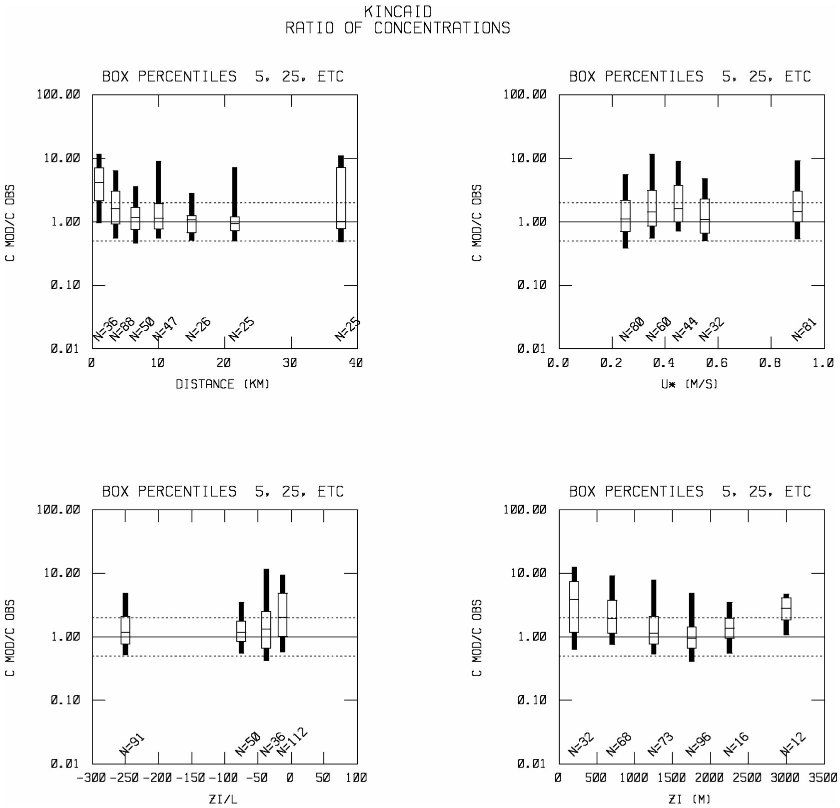

Figure 1. Residual box plots for the old plume rise scheme using data of quality 3.

The old plume rise scheme over-predicts at distances of 2km or less and to a lesser extent at distances between 2km and 5km. The old scheme also shows a tendency to over-predict at large distances. The new scheme performs well at all ranges including near source, with a large proportion of the residuals lying within the factor of two lines.

The residuals show no apparent dependence on wind speed (represented by u_*) for either of the plume rise schemes.

The old scheme tends to over-predict in neutral conditions. Figure 2 shows that the new scheme performs better in neutral conditions with less suggestion that the residuals have some dependence on stability.

Both schemes appear to have a problem with shallow mixing heights of 400m or less and with large mixing heights of more than 2500m. The new scheme under-predicts for both shallow and deep mixing depths whereas the old scheme suffers from the inverse problem with large over-prediction at small and large mixing heights.

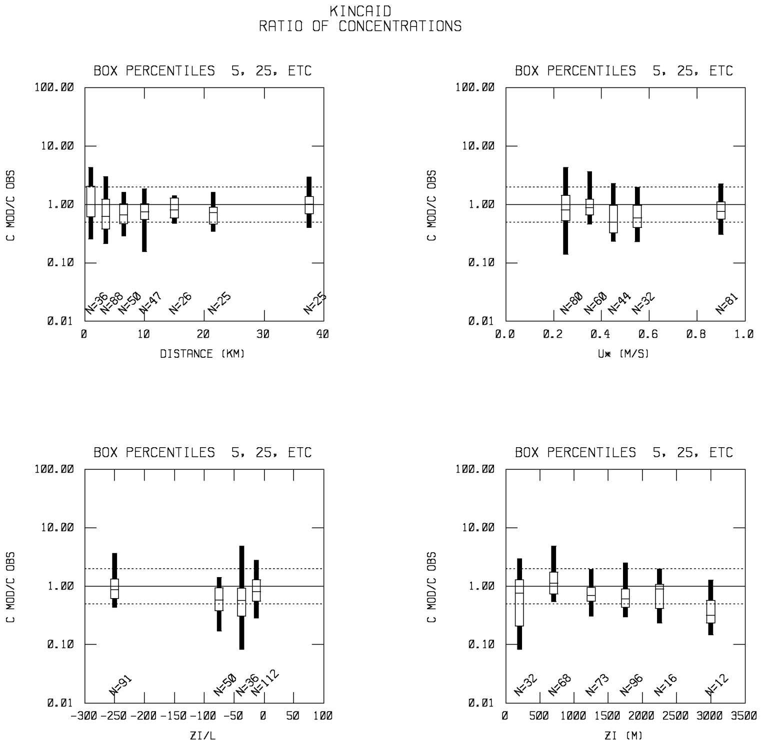

Figure 2. Residual box plots for the new plume rise scheme using data of quality 3.

COMPARING THE PERFORMANCE OF NAME WITH OTHER ATMOSPHERIC DISPERSION MODELS

In order to put the performance of NAME with the new plume rise scheme in context, it is appropriate to compare its performance with other atmospheric dispersion models. In doing this, we adopt the protocol recommended with the Model Validation Kit (*Olesen, H.R.,* 1994).

The performance of NAME is compared in Table 2 against a number of leading atmospheric dispersion models: HPDM (Earth Tech., USA), ADMS (CERC, UK), OML (NERI, Denmark), AERMOD (USA) and ISCST (EPA, USA). The data for HPDM and OML are obtained from the model validation exercise at Mol (*Olesen, H.R.,* 1995). The statistics for ADMS 3, AERMOD and ISCST are reproduced from the ADMS validation summary (*CERC,* 1999).

Table 2. Performance statistics from model assessments using data of quality 3

Model	mean	σ	bias	NMSE	r	FB	FS	FA2
Observations	54.34	40.25	0.0	0.0	1.0	0.0	0.0	1.0
HPDM	44.84	38.55	9.50	0.75	0.441	0.192	0.043	0.565
OML	47.45	45.48	6.89	1.24	0.146	0.135	-0.122	0.547
ADMS 3	51.7	34.7	2.7	0.6	0.45	0.05	0.15	0.67
AERMOD	21.8	21.8	32.6	2.1	0.40	0.86	0.59	0.29
ISCST3	30.0	60.0	24.3	2.8	0.26	0.58	-0.39	0.28
NAME	38.7	47.2	15.6	1.45	0.272	0.335	-0.159	0.562

A variety of pre-processing methods for the meteorological data have been adopted and the Kincaid data set has been used by some models for development purposes. Consequently, the validation exercise does not constitute an independent test of the models and results should therefore be treated with caution. However, the following general conclusions can be drawn.

AERMOD and ISCST show significant under estimates. NAME also shows a degree of under-prediction. Early versions of ADMS showed substantial over estimates but ADMS 3 performs well. The fraction of NAME predictions within a factor of two of observations is highly respectable. Correlation, however, is disappointingly low, Statistical measures of mean, standard deviation, bias, NMSE, FB, FS are similar to other atmospheric dispersion models.

CONCLUSIONS

The conservation equations of mass, momentum and heat used by ADMS to calculate plume rise have been introduced successfully into a Lagrangian particle model framework. Despite insufficient available meteorological data, NAME has been successfully assessed against the Kincaid data set. This validation work has shown that the new (conservation equation) plume rise scheme is superior to the old (Briggs formula) scheme. The new scheme has been successfully applied in a variety of meteorological conditions although the Kincaid data set does not enable the testing of the new scheme against very stable conditions. For observational data of quality 3, the performance of the new plume rise scheme is good.

Results from other model validation exercises using the Kincaid data set have been used to compare the performance of NAME with other atmospheric dispersion models. We conclude that with the conservation equation plume rise scheme, NAME, which historically has been a medium to long range model, is on a par with other models at short ranges.

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