Transactions on Ecology and the Environment vol 21, © 1998 WIT Press, www.witpress.com, ISSN 1743-3541

About the plume rise description and its interaction with the mixing height in the dispersion code SAFE_AIR

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Abstract

Recently, we have added some improvements about the simulation of the plume rise phenomenon to SAFE_AIR, a code simulating the transport and diffusion of airborne pollutants. This code is based on the advection of Gaussian segments and puffs driven by a 3D diagnostic wind model and is able to deal with both non-stationary and non-homogeneous conditions. We have evaluated this new version of the SAFE_AIR code against the Kincaid data set. Here we present the results obtained simulating the plume rise phenomenon using both the formulae recommended by Briggs and the Moore method, and applying three different options to simulate the interaction between the plume and thermal discontinuities in each of the two cases.

1 Introduction

We present an evaluation, performed following Hanna [1], of the last version of the SAFE_AIR code (for a description of this code see Canepa et al. [2] in the same book). In this new version of the code we have added some improvements about the simulation of plume rise phenomenon, in more detail: i) in stable atmosphere, the code treats separately the cases of windy and calm conditions both for jet and buoyant plumes using Briggs formulae [3]; ii) some approximations already done in the numerical formulation of the Moore model [4] have been avoided; iii) the Pierce method [5] to make able the code to decide automatically the use of either the buoyant plume or the jet formulae to describe the plume rise has been inserted; iv) the simulation of the stack tip downwash phenomenon has been improved introducing the possibility for the user to choice between the Bjorklund and Bowers [6] and the Briggs methods [7]; and v) a simple method for the simulation of building downwash has been implemented (Briggs, [7]; Hanna et al., [8]; Hosker, [9]). We emphasised the evaluation of the plume rise parameterisation and the interaction of the plume with thermal discontinuities, such as the top of the mixed layer, so we have chosen the Kincaid data set (Bowne and Londergan, [10]), dealing with a very buoyant plume.

2 Performed simulations

The Kincaid power plant (Illinois, USA) has a 187 m stack with a diameter of 9 m releasing a very buoyant plume. The Kincaid data set represents relatively homogeneous situations; there is no complex terrain, nor any recognised disturbance by individual buildings (Olesen, [11]). In fact, using the algorithm recently implemented in the SAFE_AIR code for the simulation of the building downwash phenomenon, we have found that the building near the source doesn't affect the plume rise because it is too far away from the source itself and it isn't high enough in comparison with the stack. The issues we consider in this exercise concern the ability of the model to predict hourly arcwise maximum concentrations. A quality indicator Q, denoting how reliable the arcwise maximum should be considered, has been assigned to each monitoring arc of the Kincaid experiment. As suggested by Olesen [12], in our analysis we have used only the data with Q equal to 3 (338 observations); therefore we have treated only data measured in neutral and unstable atmosphere, mostly in daytime hours.

The assumptions concerning input data for the SAFE_AIR code are as follows. The SAFE_AIR meteorological preprocessor (the WINDS code) has calculated the wind field making only use of data measured at a ground station situated at 10 m a.g.l. in proximity of the stack for a roughness length of 0.1 m. As suggested by Olesen [12], the observed mixing height has been used. All the simulations we have performed made use of the Brookhaven σ-function, which has given the best results in many previous tests (Canepa and Ratto, [13]; Canepa et al., [14]; Canepa et al., [15]). About the reflection terms we have assumed that when the centre of the element is inside the mixed layer, only one total reflection at the ground and one total reflection at the top of the mixed layer are computed; when the centre of the element is above the mixed layer, only one total reflection at the ground is computed. We have placed in the SAFE_AIR domain a polar grid of receptors at the same distances as the Kincaid arcs themselves with a regular angular spacing of four degrees.

To evaluate the plume rise parameterisation we have performed the simulations of the Kincaid experiment using both the Briggs method [3] and the Moore method [4] to calculate the final plume rise (indicated, respectively, as B and M hereafter). In both cases we have simulated the stack tip downwash phenomenon using the Bjorklund and Bowers [6] method, even if the phenomenon is seldom simulated because the experimental data we have used were mostly measured during low wind conditions. For each plume rise method we have tested three different options to describe the interaction between the plume and thermal discontinuities: 1) total penetration of the plume aloft without taking into account the different atmospheric stratification above the mixed layer; 2) total penetration imposing slightly stable condition above the mixed layer; 3) Turner [16] partial penetration method imposing again slightly stable condition above the mixed layer (indicated, respectively, as (1), (2), and (3) hereafter). So we performed a total of 6 simulation sets.

3 Model performances evaluation

Table 1 summarises some important statistical parameters concerning our results. Looking at MEAN, BIAS (defined as $\overline{C_O} - \overline{C_M}$), and FB values it is possible to deduce that the SAFE_AIR code underestimates on average the measured concentrations using the Briggs method and overestimates on average them using the Moore method for the simulation of the plume rise phenomenon apart from we used (1), (2) or (3) assumptions. The mean underestimation amount is bigger than the overestimation one. In fact in low wind conditions, as in a lot of the experimental situations we have simulated, the Briggs method predicts plume rise values bigger than those predicted using the Moore method

Table 1: Statistics for maximum arcwise normalised concentrations (unit 10^{-9} s m^{-3}).

Model	MEAN	SIGMA	BIAS	NMSE	COR	FA2	FB	FS
C_OBS	54.34	40.25	0.00	0.00	1.000	1.000	0.000	0.000
B(1)	41.87	45.20	12.46	1.70	-0.016	0.399	0.259	-0.116
M(1)	59.73	52.54	-5.39	1.10	0.201	0.497	-0.095	-0.265
B(2)	37.67	47.42	16.67	2.34	-0.167	0.349	0.362	-0.164
M(2)	56.98	53.64	-2.64	1.36	0.071	0.488	-0.047	-0.285
B(3)	45.36	53.96	8.98	1.98	-0.062	0.402	0.180	-0.291
M(3)	59.37	62.64	-5.03	1.55	0.112	0.459	-0.089	-0.435

giving rise to lower ground level simulated concentrations. Nevertheless, analysing in more detail the simulated concentration values (not reported here for the sake of brevity) some zero simulated concentrations near the source can be observed using both methods; these are predicted by the model when the plume rise phenomenon is particularly effective. From SIGMA and FS values we can argue that using the SAFE_AIR code the spreading of the simulated concentration values is bigger than that of the observed ones, especially using the M(3) assumptions. On the other hand NMSE, COR, and FA2 indices provided the best results using the M(1) assumptions. Examining the statistical quantities as a whole, we can observe that, as the code performance is concerned, the choice of the plume rise parameterisation in most relevant with respect to both the choice of the stability conditions above the mixed layer and the description of the interaction between plume rise and top of the mixed layer. On the whole, the Moore method yields better results than the Briggs method. Pointing the attention on the Moore method, there are not any statistical indices indicating that the Turner partial penetration method gives best results with respect to the assumption of non interaction between plume rise and top of the mixed layer.

Figure 1 displays the quantile-quantile plots of the data. The differences between the two plume rise parameterisation to calculate the final plume rise are more evident at lowest simulated concentration values. These plots reveal again the tendency of the model towards both underprediction using the Briggs method and overprediction using the Moore method. Looking at the quantile-quantile plots concerning assumptions (3), we can confirm the greater spreading of the simulated concentration values in comparison with that of the observed one with respect to the cases concerning assumptions (1) and (2).

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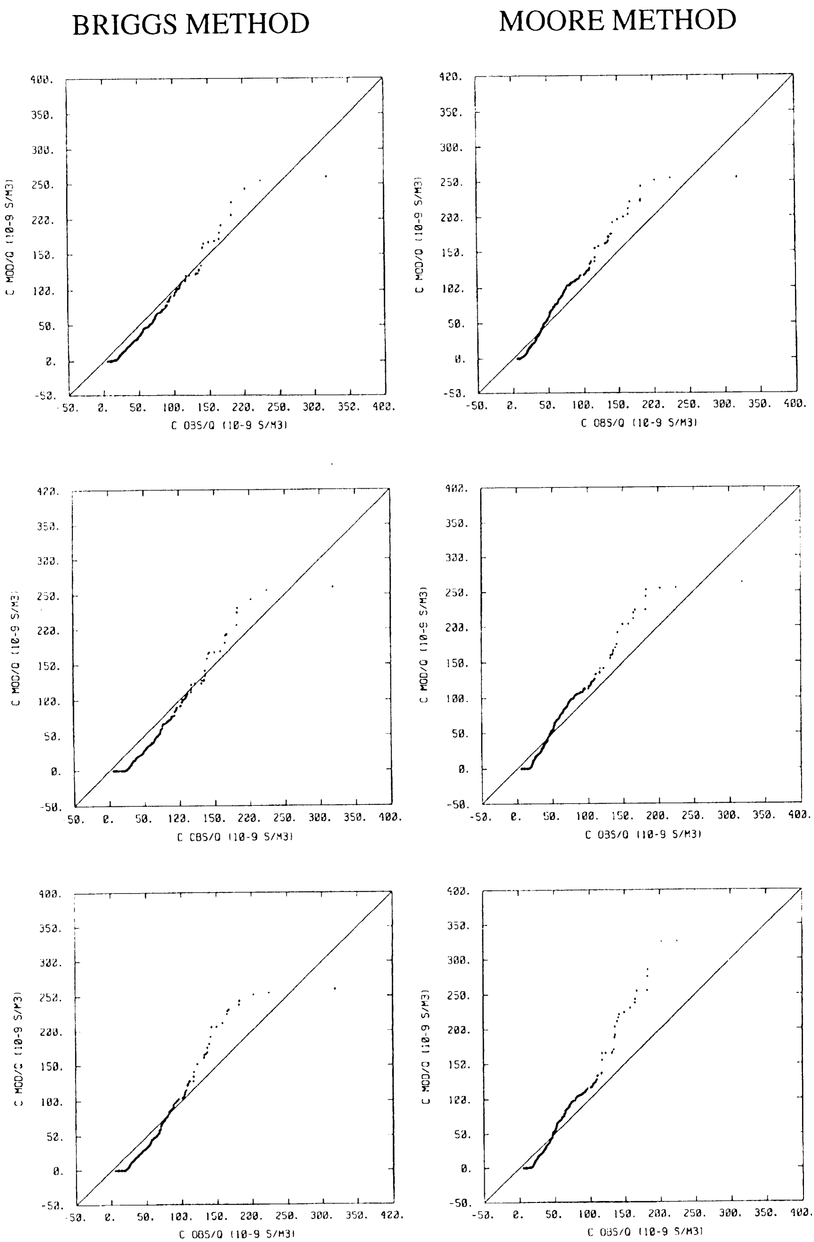

Figure 1: Quantile-quantile plots: normalised simulated concentrations versus normalised observed concentrations, unit 10^{-9} s m^{-3} (assumptions (1) on the top, assumptions (2) in the centre, assumptions (3) at the bottom).

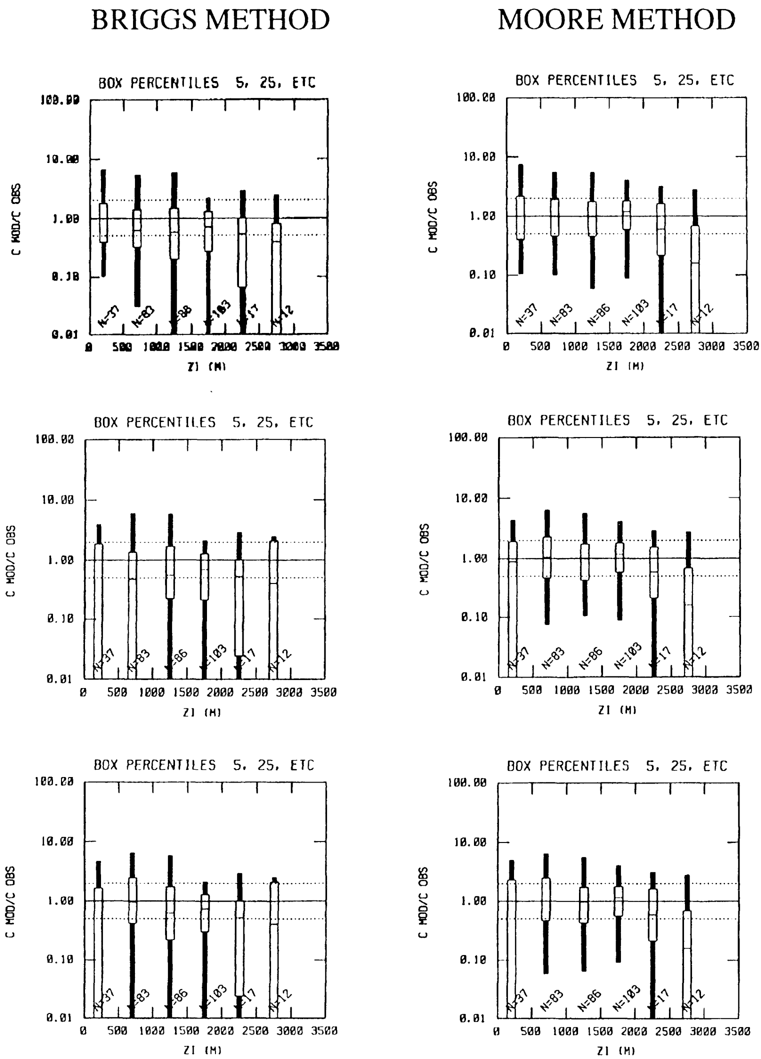

Figure 2: Box plots of the ratio C_M/C_0 analysed in terms of mixing height (assumptions (1) on the top, assumptions (2) in the centre, assumptions (3) at the bottom).

For diagnosing model behaviour with respect to the mixing height, six box plots (one for each assumption set) have been prepared: they are reproduced in Figure 2. In each case, the data have been stratified according to the mixing height: six subsets has been formed. Each subset contains a definite number of C_M and C_O pairs. For each pair, the ratio C_M / C_O has been determined. In order to reduce 'noise', a filter has been imposed on the data presented in the box plots: when both the observed and the predicted concentration values are small (normalised concentration less than 15×10^{-9} s m^{-3}), the ratio is assumed to be unity (in our exercise this filter was imposed ten times using the Moore method and eleven times using the Briggs method). The box plots display the distribution of this ratio. The boxes indicate percentiles 5, 25, 50, 75 and 95. For a physically correct model, performance should not show a trend with mixing heights. Looking at the box plots we can deduce some characteristics of the SAFE_AIR code behaviour indeed. The box plot concerning assumptions M(1) shows the most satisfactory results even if there is a relevant tendency towards underestimation of the measured concentrations for the highest mixing heights. The box plot concerning assumptions B(1) shows the same relevant tendency towards underestimation for the highest mixing heights as the previous one, beside there is a generalised tendency towards underestimation. The same behaviour is confirmed by the box plots concerning both B(2) and B(3) assumptions where the underestimation is some more evident for the lowest mixing heights. The box plots concerning both M(2) and M(3) assumptions show a quite satisfactory behaviour for intermediate values of the mixing height, but relevant underestimation both for the lowest and the highest values of the mixing height.

4 Conclusions

We have presented an evaluation of the last version of the SAFE_AIR code against the Kincaid data set. We have tested both the Briggs and the Moore methods to simulate the plume rise phenomenon. In both cases we have taken into account the stack tip downwash phenomenon using the Bjorklund and Bowers method. For each plume rise method we have tested three different options to describe the interaction between the plume and thermal discontinuities, such as the top of the mixed layer. As the code performance is concerned, the choice of the plume rise parameterisation in most relevant with respect to both the choice of the stability conditions above the mixed layer and the description of the interaction between plume rise and top of the mixed layer. The Moore method for the simulation of the plume rise phenomenon has performed better than the Briggs one which has given too high plume rise predictions in low wind conditions. On the whole we obtained the most satisfactory results using at the same time: the plume rise Moore method, the total penetration option of the plume aloft the mixing height, and without taking into account the different atmospheric stratification above the mixed layer; that means the simplest assumption with respect to the interaction with thermal discontinuities. Nevertheless, we have observed an undesirable dependence on the mixing height values of the code performances.

We are going to direct our future efforts towards a deeper investigation of the simulation of the plume rise phenomenon in low wind conditions. Furthermore, we are going to study some more deeply the interaction of the plume with the top of the mixed layer introducing criteria to take into account both the plume penetration above the top of the mixed layer and the subsequent plume rise in the upper elevated stable layer.

Acknowledgements

We want to thank Prof. A. Longhetto and Dr. P. Zannetti for a constant help in the work in which this particular topic is inserted. We also want to thank Drs. D. Anfossi, N. Arena, F. Modesti, and G. Tinarelli for many fruitful discussions and helpful suggestions. We are particularly indebted to Dr. J.S. Touma for providing us with useful documents.

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