J. ENVIRONMENTAL SYSTEMS, Vol. 26(1) 27-39, 1997-98

MODELING AND EVALUATION OF DISPERSION PARAMETERS FOR ODORS FROM AGRICULTURAL SOURCES

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ABSTRACT

This article presents an evaluation of four models that are widely used in developing Gaussian plume models, based on the atmospheric stability class and the Pasquill-Gifford curves. The four statistics used to evaluate the models are the sum of residuals, the minimized sum of the squared residuals, the correlation coefficient, and the estimated error standard deviation. Evaluation shows that all of the four models have problems in fitting the Pasquill-Gifford data when the downwind distance increases from the source. A new model has been developed which fits the Pasquill-Gifford data more effectively than the previously developed models studied.

INTRODUCTION

The Gaussian plume model is the most common air pollution model. It has been used extensively in the atmospheric sciences to predict atmospheric diffusion [1-7] as well as in agricultural engineering for odor emission problems [8-11]. However, a correct calculation of the dispersion parameters σ_y and σ_z in the Gaussian plume model is necessary. The quantities σ_y and σ_z represent the crosswind and vertical standard deviations of the dispersing plume respectively, and are functions of the atmospheric stability class and the downwind

doi: 10.2190/6CKR-LJRB-UMAD-J7UC
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distance of the receptor from a source. Many models of the dispersion parameters have been developed [12-15]. These models are widely used in developing Gaussian plume models. The following questions arise for research in agricultural odor dispersion: Which model is the best to use and how should the prediction models be compared if the models for dispersion parameters are different?

The objectives of this research were 1) to evaluate four models using the dispersion parameters σ_y and σ_z based on the atmospheric stability class and the Pasquill-Gifford curves, and 2) to develop a new model, which is simple in form and fits the Pasquill-Gifford curves more effectively.

ATMOSPHERIC STABILITY AND PASQUILL-GIFFORD CURVES

One of the major meteorological factors that affect odor pollution phenomena is atmospheric stability. Atmospheric stability categorizes the turbulent status of the atmosphere and affects the dilution rate of odor. Pasquill characterized atmospheric stability using six classes based on the incoming solar radiation, the cloud amount at night, and the wind speed: A, very unstable; B, unstable; C, slightly unstable; D, neutral; E, slightly stable; F, stable (Table 1) [16].

The Pasquill-Gifford curves are families of curves of σ_y and σ_z as functions of the atmospheric stability class and the downwind distance (see Figures 1 and 2). The curves are used as the base reference to evaluate four models of the dispersion parameters σ_y and σ_z because they are the most used formulation for U.S. EPA regulatory modeling applications [5].

Table 1. Stability Categories [3]

	Day, Incoming Solar Radiation			Night, Cloudiness	
Wind velocity (m/s)	Strong	Moderate	Slight	Thin Overcast or ≥0.5 Cloudiness	≤0.4 Cloudiness
<2	A	A-B	B	—	—
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	D
5-6	C	C-D	D	D	D
>6	C	D	D	D	D

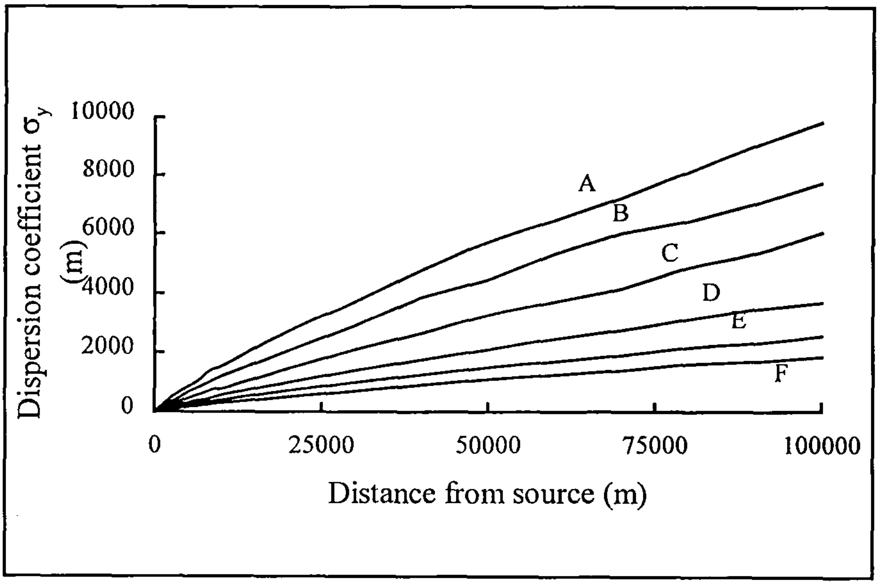

Figure 1. The Pasquill-Gifford curves for σ_y.

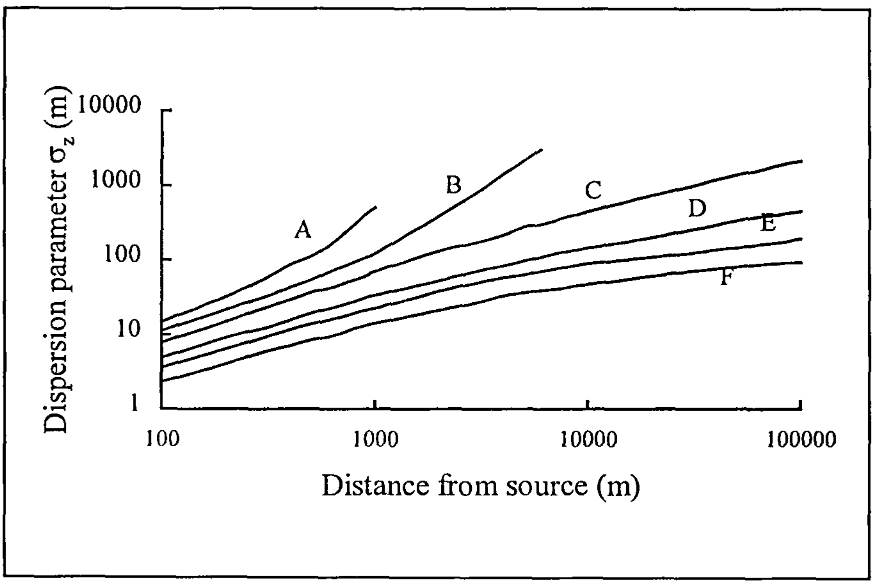

Figure 2. The Pasquill-Gifford curves for σ_z.

MODELS OF THE DISPERSION PARAMETERS

Model 1

Green et al. [12] proposed an analytical form for the dispersion parameters σ_y and σ_z, as:

$$\sigma_y(x) = \frac{k_1 x}{[1 + (x/k_2)]^{k_3}}$$

$$\sigma_z(x) = \frac{k_4 x}{[1 + (x/k_2)]^{k_5}} \tag{1}$$

where the constants k_1, k_2, k_3, k_4, and k_5 are given in Table 2.

Model 2

Smith [10] used the following form of the Pasquill-Gifford curves obtained by Bowers et al. [13] for ground level agricultural sources:

$$\sigma_y = 0.84678x \tan(k_1 \text{-} k_2 \ln x)$$

$$\sigma = k_3 x^{k_4} \tag{2}$$

where constants k_1, k_2, k_3, and k_4 depend on the prevailing atmospheric stability [17] (Tables 3 and 4). The constants k_3 and k_4 also depend on the downwind distance x. A similar form of Equation (2) can also be found in Turner's Workbook of Atmospheric Dispersion Estimates [6].

Model 3

McMullen [14] proposed an analytical expression for σ_y and σ_z as:

$$\sigma_y = e^{k_1 + k_2 \ln x + k_3 (\ln x)^2}$$

$$\sigma_z = e^{k_4 + k_5 \ln x + k_6 (\ln x)^2} \tag{3}$$

Table 2. Coefficients in Equation (1)

Stability Class	k_1	k_2	k_3	k_4	k_5
A	0.250	927	0.189	0.1020	–1.918
B	0.202	370	0.162	0.092	–0.101
C	0.134	283	0.134	0.0722	0.102
D	0.0787	707	0.135	0.0475	0.465
E	0.0566	1070	0.137	0.0335	0.624
F	0.0370	1170	0.134	0.0220	0.700

Table 3. Piecewise Coefficients in Equation (2) for σ_z [17]

Stability Class	Distance, x	k_3	k_4
A	0-150	0.1087	10.542
	150-200	0.08942	1.0932
	200-250	0.07058	1.1262
	250-300	0.03500	1.2644
	300-400	0.01531	1.4094
	400-500	0.002265	1.7283
	>500	0.0002028	2.1166
B	100-200	0.1451	0.93198
	200-400	0.1105	0.98332
	>400	0.05589	1.0971
C	All	0.1103	0.91465
D	0-300	0.08474	0.86974
	300-1000	0.1187	0.81066
	1000-3000	0.3752	0.64403
	3000-10000	0.5125	0.60486
E	0-300	0.08144	0.81956
	300-1000	0.1162	0.75660
	1000-2000	0.2771	0.63077
	2000-4000	0.4347	0.57144
	4000-10000	0.7533	0.50527
F	0-200	0.05437	0.81588
	200-700	0.06425	0.78407
	700-1000	0.1232	0.68465
	1000-2000	0.1770	0.63227
	2000-3000	0.3434	0.54503
	3000-7000	0.6523	0.46490

Table 4. Coefficients in Equation (2) for σ_y [17]

Stability Class	k_1	k_2
A	0.72722	0.044216
B	0.53814	0.031583
C	0.34906	0.018949
D	0.23270	0.012633
E	0.17453	0.009475
F	0.11636	0.006317

Table 5 gives the coefficients k_1, k_2, k_3, k_4, k_5, and k_6 for Equation (3).

Model 4

Carney and Dodd [9] calculated the odor dispersion from a slurry store using a power law function for both σ_y and σ_z:

$$\sigma_y = k_1 x^{0.903}$$
$$\sigma_z = k_2 x^{k_3} \tag{4}$$

where the values of k_1, k_2, and k_3 are given in Table 6. As shown in Table 6 the values of k_2 and k_3 vary with the downwind distance from a source.

Model 5

A new model is proposed in this article. This model is simple in form, and is expected to fit the Pasquill-Gifford curves best among the five models presented:

$$\sigma_y = k_1 + k_2 x^{k_3}$$
$$\sigma_z = k_4 + k_5 x^{k_6} \tag{5}$$

Table 5. Coefficients in Equation (3)

Stability Class	k_1	k_2	k_3	k_4	k_5	k_6
A	5.357	0.883	−0.0076	6.035	2.1097	0.2770
B	5.058	0.902	−0.0096	4.694	1.0629	0.0136
C	4.651	0.918	−0.0076	4.110	0.9201	−0.0020
D	4.230	0.922	−0.0087	3.414	0.7371	−0.0316
E	3.922	0.922	−0.0064	3.057	0.6794	−0.0450
F	3.533	0.918	−0.0070	2.621	0.6564	−0.0540

Table 6. Coefficients in Equation (4) [15]

Stability Class	$x < x_1$			x_1	$x_1 < x < x_2$		x_2	$x < x_2$	
	k_1	k_2	k_3		k_2	k_3		k_2	k_3
A	0.400	0.125	1.030	250	0.0099	1.510	500	0.000226	2.10
B	0.295	0.119	0.986	1000	0.0579	1.090	10000	0.05979	1.09
C	0.200	0.111	0.911	1000	0.111	0.911	10000	0.111	0.911
D	0.130	0.105	0.827	1000	0.392	0.636	10000	0.948	0.540
E	0.098	0.100	0.778	1000	0.373	0.587	10000	2.85	0.366

Table 7. Coefficients in Equation (5)

Stability Class	k_1	k_2	k_3	k_4	k_5	k_6
A	−32.895	1.069	0.792	23.116	1.608×10^{-5}	2.492
B	−49.563	0.896	0.788	24.556	1.606×10^{-4}	1.923
C	15.792	0.259	0.871	−35.099	1.175	0.653
D	−12.616	0.328	0.811	−23.068	2.464	0.457
E	−14.619	0.356	0.771	−40.434	10.877	0.263
F	−11.067	0.208	0.791	−30.551	10.296	0.218

where the coefficients k_1, k_2, k_3, k_4, k_5, and k_6 are listed in Table 7. These coefficients were obtained using the non-linear parameter estimation based on the Levenburg-Marquardt algorithm [18].

STATISTICS USED TO EVALUATE EACH MODEL

Four statistics were used to evaluate the goodness of each model:

1. sum of residuals, $\Sigma\varepsilon$, which is expected to be zero for a perfect model;
2. minimized sum of the squared residuals, S, which is the best indicator of fit among several non-linear models [19];
3. correlation coefficient, R^2, which is expected to be unity for a perfect model; and
4. estimated error standard deviation, S_e. A large value for the estimated error standard deviation may be an indication of a larger random error component or of an improper specification for the model [20].

RESULTS AND DISCUSSION

Evaluation of the Models

Table 8 shows the statistical indices calculated for the five models of the dispersion parameter σ_y, including the new model developed in this article. It is seen that model 1 is better than models 2, 3, and 4 for classes A, B, C, and E because it has the smaller sum of residuals, minimized sum of the squared residuals, estimated error standard deviation, and a near unity correlation coefficient. Model 3 was best compared to models 1, 2, and 4 for classes D and F. However, the new model 5 is the best overall because it has the smallest sum of residuals, minimized sum of the squared residuals, estimated error standard deviation, and the highest correlation coefficient for all classes, compared to models 1 to 4.

Table 8. Comparison of Statistics of Five Models for σ_y

		$\Sigma\varepsilon$	S	R^2	S_e
Class A	Model 1	−2936.08	1171313.25	1.00	220.92
	Model 2	−2928.42	1375038.25	0.99	234.52
	Model 3	−3908.34	2263167.50	0.99	307.08
	Model 4	−16392.61	37863996.00	0.86	1230.67
	Model 5	5.12×10^{-5}	45713.61	1.00	43.58
Class B	Model 1	−1425.01	575194.69	1.00	154.81
	Model 2	−1816.18	792974.88	1.00	178.10
	Model 3	−3468.10	1955123.50	0.99	285.42
	Model 4	−8541.98	11674367.00	0.93	683.36
	Model 5	-9×10^{-9}	107487.56	1.00	65.57
Class C	Model 1	−1310.78	304110.88	1.00	112.57
	Model 2	−1383.13	385442.44	1.00	124.17
	Model 3	−1504.70	388297.72	1.00	127.20
	Model 4	−3113.30	1647805.50	0.98	256.73
	Model 5	-3.7×10^{-5}	59306.53	1.00	48.71
Class D	Model 1	−1229.59	327188.88	0.99	116.76
	Model 2	−1458.07	438136.25	0.99	132.38
	Model 3	−1193.58	288226.31	0.99	109.59
	Model 4	−2021.72	901900.44	0.98	189.94
	Model 5	1.16×10^{-5}	7145.71	1.00	16.91
Class E	Model 1	−2196.04	814561.38	0.95	184.23
	Model 2	−2253.35	875639.94	0.95	187.15
	Model 3	−2398.99	984673.38	0.94	202.55
	Model 4	−2808.53	1415322.50	0.92	237.93
	Model 5	4.85×10^{-5}	3039.98	1.00	11.03
Class F	Model 1	−491.41	83650.95	0.99	59.04
	Model 2	−473.41	82379.70	0.99	57.40
	Model 3	−466.26	75476.65	0.99	56.08
	Model 4	—	—	—	—
	Model 5	3×10^{-7}	3947.66	1.00	12.57

Table 9 shows the statistical indices calculated for the five models presented for the dispersion parameter σ_z. It is seen that model 3 is the best compared to models 1, 2, and 4 for classes A, D, and F. Model 1 is the best compared to models 2, 3, and 4 for class B. Model 4 is the best for classes C and E. The new model 5 is the best overall for classes A, B, C, D, and E, but was inferior for class F. Overall, model 5 is recommended for the calculation of dispersion parameters σ_y and σ_z. It

Table 9. Comparison of Statistics of Five Models for σ_z

		$\Sigma\varepsilon$	S	R^2	S_e
Class A	Model 1	1328.10	1333612.63	0.82	436.48
	Model 2	1160.41	1069315.63	0.86	365.60
	Model 3	1148.69	896917.88	0.88	357.95
	Model 4	1194.69	1143033.38	0.85	377.99
	Model 5	-2.6×10^{-6}	679.37	1.00	9.85
Class B	Model 1	5233.50	8182300.50	0.39	862.46
	Model 2	5838.63	9851823.00	0.29	906.08
	Model 3	5252.55	8223683.00	0.39	864.64
	Model 4	5250.87	8258501.50	0.39	829.58
	Model 5	8.3×10^{-5}	1649.84	1.00	11.73
Class C	Model 1	−10884.68	15608620.00	0.09	806.45
	Model 2	−9862.15	13589746.00	0.17	737.29
	Model 3	−9488.31	12535834.00	0.22	722.72
	Model 4	−9009.23	11593018.00	0.27	680.97
	Model 5	2.4×10^{-5}	4023.92	1.00	12.69
Class D	Model 1	19.21	2419.84	1.00	10.04
	Model 2	−318.15	26754.01	0.96	32.71
	Model 3	−34.48	1409.06	1.00	7.66
	Model 4	−59.27	3134.84	0.99	11.20
	Model 5	4.4×10^{-5}	700.31	1.00	5.29
Class E	Model 1	21.47	885.19	0.99	6.07
	Model 2	−273.73	17328.95	0.83	26.33
	Model 3	27.82	734.03	0.99	5.53
	Model 4	31.20	643.47	0.99	5.07
	Model 5	-2.3×10^{-6}	304.56	1.00	3.49
Class F	Model 1	3.78	82.83	1.00	1.86
	Model 2	−224.72	7263.63	0.74	17.05
	Model 3	15.42	38.11	1.00	1.26
	Model 4	—	—	—	—
	Model 5	1.4×10^{-5}	103.78	1.00	2.04

is also seen that the piece-wise functions of x used in models 2 and 4 are inconvenient to use practically, and they do not yield better results than the other models.

Observations by comparing the Pasquill-Gifford data with the predicted values using models 1 to 4 with the Pasquill-Gifford curves for σ_y indicate that for classes A and B, all models are capable of fitting the Pasquill-Gifford data for the downwind distance x < 10000 m; model 4 begins to fail when x > 25000 m, and the other three models begin to fail when x > 50000 m. Similar conclusions can be drawn for classes C, D, and F. For class E, the predicted results from all models tend to be larger than the Pasquill-Gifford data when x > 20000 m.

Observations by comparing the Pasquill-Gifford data with the predicted values using models 1 to 4 with the Pasquill-Gifford curves for σ_z indicate that for class A, every model was capable of fitting the Pasquill-Gifford data with distances (x) between 100 m and 1000 m. For class B, the predicted results of all models are smaller than the Pasquill-Gifford data for x > 2000 m. No model could fit the Pasquill-Gifford data effectively for class C when x > 20000 m. For class D, every model was capable of fitting the Pasquill-Gifford data for x < 10000 m but no model was good for x > 20000 m. For classes E and F, model 2 yields the largest error when x > 10000, while the other three models agree well with the Pasquill-Gifford data.

Further Development of the New Model

All five models were developed over a distance far in excess of the importance for odor dispersion from agricultural sources. Measurements show that the downwind distance affected by agricultural odor sources is usually within 5000 m [11, 21, 22]. Therefore, this distance is assumed to be the maximum distance that

Table 10. Coefficients of Model 5 for Downwind Distances Between 100 and 5000 m

	Stability Class	k_1	k_2	k_3
σ_y	A	−13.273 (7.531)*	0.714 (0.136)	0.835 (0.022)
	B	−1.428 (8.931)	0.364 (0.121)	0.880 (0.038)
	C	−12.778 (1.684)	0.279 (0.024)	0.873 (0.009)
	D	−4.119 (2.404)	0.215 (0.038)	0.857 (0.020)
	E	−3.241 (1.609)	0.143 (0.023)	0.874 (0.018)
	F	−0.78 (0.688)	0.082 (0.008)	0.891 (0.012)
		k_4	k_5	k_6
σ_z	A	23.161 (6.645)	1.61×10^{-5} (1.37×10^{-5})	2.492 (0.124)
	B	22.977 (4.588)	0.000189 (4.13×10^{-5})	1.904 (0.026)
	C	−2.240 (3.886)	0.185 (0.061)	0.857 (0.038)
	D	−5.057 (1.094)	0.516 (0.075)	0.619 (0.016)
	E	−5.218 (1.951)	0.590 (0.191)	0.559 (0.036)
	F	−2.726 (0.893)	0.397 (0.099)	0.537 (0.027)

*Standard deviation

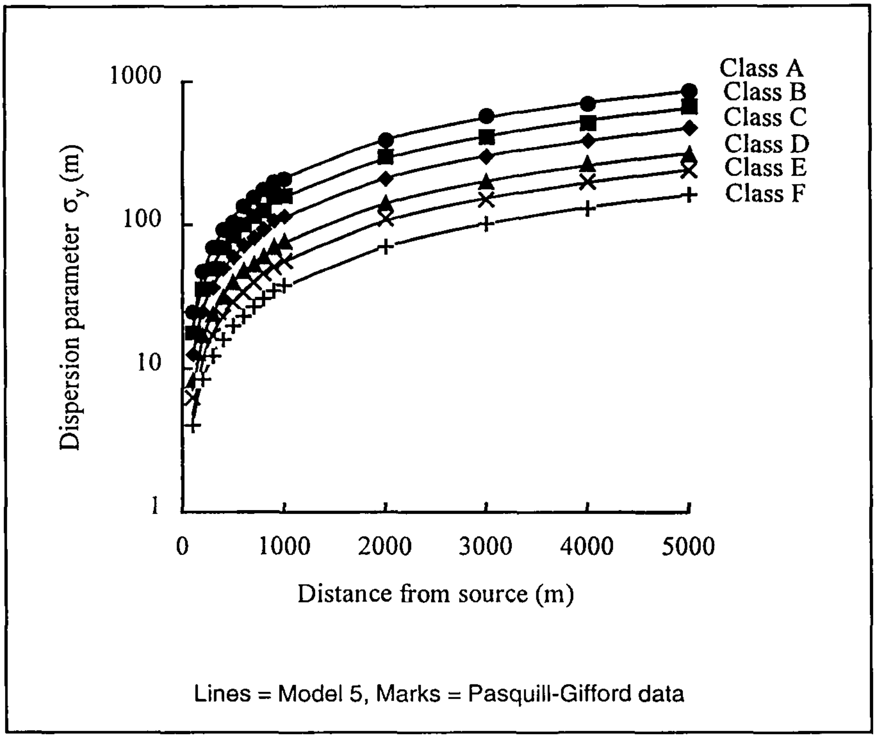

Figure 3. Comparison of model 5 with the Pasquill-Gifford data for σ_y.

agricultural odors would disperse from a source. Re-estimation of the new coefficients for model 5, allicable for $100 \leq x \leq 5000$ m, is shown in Table 10.

Figures 3 and 4 show a comparison of the predicted results with the Pasquill-Gifford data for σ_y and σ_y respectively. It is seen that the new model 5 gives very good fit to the Pasquill-Gifford data.

CONCLUSIONS

The following conclusions were drawn from this research:

1. Evaluation of four widely used models of the dispersion parameters shows that all of the models have problems in fitting the Pasquill-Gifford data;
2. There is no need to use the piece-wise functions of x for modeling σ_y and σ_z; and
3. A new model was developed which fits the Pasquill-Gifford data best.

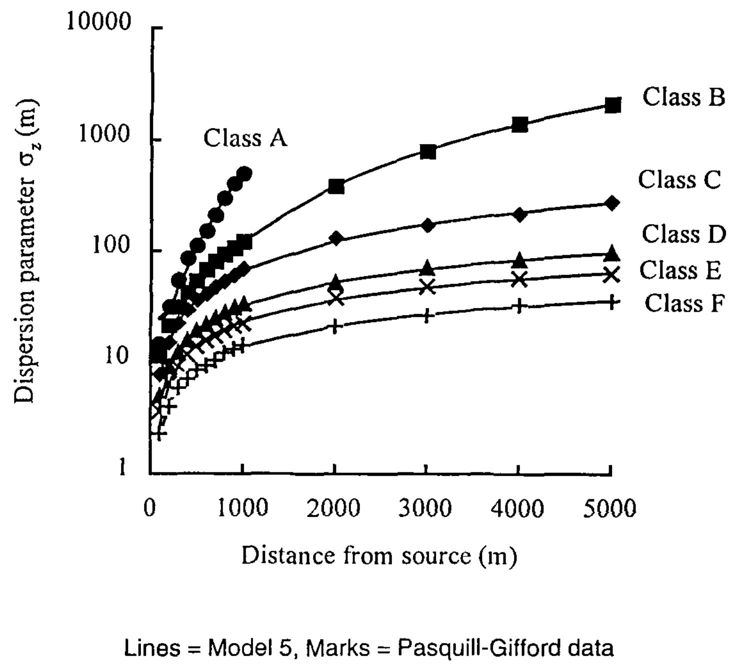

Figure 4. Comparison of model 5 with the Pasquill-Gifford data for σ_z.

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