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THE BEHAVIOUR OF BUOYANT PLUMES IN NEUTRAL AND STABLE CONDITIONS IN CANADA

By

H. Whaley* and G.K. Lee**

Abstract

Plume dispersion parameters obtained during six years of research by the Canadian Combustion Research Laboratory (CCRL) have been evaluated and compared to the standard predictive relationships established by Briggs and Pasquill-Gifford. The data correspond to neutral and stable conditions, Stability Class C to F but excludes any limited-mixing or layered atmosphere studies or situations where topography influences plume spread. In all, ten sources in five geographic regions were studied during Spring, Fall and Winter.

It has been shown that the plume rise data can be represented by the Briggs and Moore form of relationship for neutral conditions. The data suggest a proportionality constant of 0.87 and a levelling-off at 15 stack heights when constrained to the 2/3 power law required by the Briggs continuous model. The unconstrained regression yielded a constant of 0.5 and 0.71 power law relationship with downwind distance, between the Briggs and Moore relationships. However, both of the latter significantly overestimate the measured data.

In stable conditions the Briggs levelling-off value of 2.9 for the dimensionless plume rise is in good agreement with the findings in this paper, but this occurs at a dimensionless downwind distance of 18.4 rather than 2.4. A slight variation in the maximum plume rise with the bulk Richardson number over the dispersion zone has been noted for stable conditions.

The Pasquill-Gifford plume spread curves as modified by Bowne for rural conditions represent a convenient means of comparing the data obtained under corresponding stability and topographic conditions in Canada. The variation of measured horizontal spread parameters, σ_y with downwind distance differed significantly from the P/G curves, being wider by at least two stability classes for unstable/neutral i.e. A/B rather than C/D, and for stable, C rather than E. In the case of very stable F class, the measured σ_y values corresponded to A class, six classes wider than expected. The vertical spread parameters, σ_z were usually in agreement with P/G curves from 4 to 10 km from the source, closer to the source σ_z was greater and farther from the source σ_z was less than predicted. It was also found that the bulk Richardson number could be used to classify the plume spread parameters in a similar manner to the P/G stability classes.

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NOMENCLATURE

c_p = specific heat at constant pressure, kJ/kg °C

F = buoyancy flux = $gQ/\pi c_p T$, m^4/s

g = gravitational constant, m/s^2

h = stack height, m

L = characteristic length for a buoyant plume = $F/\bar{U}^3$, m

Q = heat emission from stack kJ/s

R_b = bulk Richardson number = $\frac{gZ_p{}^2}{4\bar{U}^2 T} \left(\frac{\partial\Theta}{\partial Z}\right)$

S = stability parameters (Brunt-Vaisala-frequency)^2 (g/T ($\partial\Theta/\partial Z$), s^{-2}

T = absolute temperature of ambient air, K

$\bar{U}$ = mean wind speed over the plume height Z_p, m/s

X = downwind distance, km

$\bar{Y}$, $\bar{Z}$ = horizontal and vertical co-ordinates of the centre of mass flow, at any given cross-wind plume traverse, m

Z_p = height of plume top above terrain, m

$\overline{\Delta Z}$ = plume rise above stack top, m

$\frac{\partial\Theta}{\partial Z}$ = vertical potential temperature gradient, °C/m

ρ = density of ambient air, kg/m^3

σ_y, σ_z = horizontal and vertical standard deviations respectively, m

1.0 INTRODUCTION

Before the oil embargo of 1973, cheap, plentiful energy and progressively more stringent environmental controls led to regulations that compelled industry to utilize clean fuels such as natural gas and distillate oil in direct-fired combustion equipment. Consequently, the use of coal declined dramatically in Canada and many coal mines were closed. The advent of potential energy shortages, however, led to the realization that energy supplies were not unlimited and that increased coal use would be needed to stretch dwindling oil and gas reserves. It also focused attention on the often conflicting requirements of clean air quality criteria and efficient energy utilization.

It is against these developments that the Canadian Combustion Research Laboratory (CCRL) of the Canada Centre for Mineral and Energy Technology (CANMET), plume dispersion research program was developed. The main objective of this program was to provide atmospheric dispersion parameters that could be used with confidence by the energy processing industries and by environmental regulators.

2.0 THE CCRL PLUME DISPERSION RESEARCH PROGRAM

2.1. Background

A study by Whaley (1969) showed that reliable information on dispersion parameters was not available in Canada. Therefore, a comprehensive research program was undertaken by CCRL to study the atmospheric dispersion of buoyant plumes emitted from tall stacks located in various geographic regions of Canada.

An immersion probing methodology was developed which utilizes helicopter- and automobile-carried instrumentation to obtain three-dimensional data on plume dispersion. In addition, atmospheric temperature and wind vector profiles in the surface boundary layer, within and above the dispersion zone, are determined at locations both near and remote from the source. This meteorlogical data together with the synoptic weather maps provide the background information necessary for parameter correlation. Full details of the methodology have been described by Whaley (1974).

The program was jointly sponsored with industry and meteorological support was provided by the Atmospheric Environment Service (AES) of Environment Canada. To date over six years of research have been completed and studies have been conducted in all five geographic regions. Some comparative studies have been conducted on the same source during different seasons or during the same season when emissions have been reduced by pollutant control strategies. Table 1 lists the sources studied during the six- year period, together with their geographic location, relevant emission parameters and source configuration.

2.2. The derivation of plume spread parameters

The measured data obtained in the CCRL program has been evaluated numerically by a three-step procedure which employs the method of finite differences (see Whaley (1974)).

After the reconstruction of three or more cross-wind sections of the plume to show continuous SO_2 profiles, each plume contour was digitized to establish the co-ordinates of the centre of pollutant mass flow, and the standard deviations σ_y and σ_z. Downwind distance and plume rise are then determined from these values. In addition some measurements of plume rise were obtained from variable altitude traverses along the plume axis.

The importance of reliable predictions of the plume axis and vertical spread σ_z cannot be overestimated since they are key parameters in the dispersion process which in turn significantly influence ground-level impingement concentrations computed by gaussian dispersion models. A modification by Bowne (1974) of the Pasquill (1962, 1968) -Gifford, (1961) (P/G) σ_y and σ_z curves for rural conditions, together with the Briggs (1968) and Moore (1974) analyses of plume rise were used for comparative purposes in this paper.

2.3. Plume rise parameters

A comprehensive analysis of plume rise under a variety of meteorological conditions has been published by Briggs (1968). He concluded that the rise of buoyant plumes in stable and neutral conditions up to their levelling-off point can be represented by an equation of the form:

$$\overline{\Delta Z} = K \left(\frac{FX^2}{\overline{U}^3} \right)^{1/3} \qquad (1)$$

where $K = 1.6$

This equation reduces to the dimensionless relationship

$$\frac{\overline{\Delta Z}}{L} = K \left(\frac{X}{L} \right)^{2/3} \qquad (2)$$

where $L = \frac{F}{\overline{U}^3}$ is a characteristic length for a buoyant plume.

By definition the plume rise is that portion of the plume axis between the stack top and the levelling-off point. In general the term plume rise becomes inappropriate beyond about 2 km from the source because of differential dispersion rates and assimulation of plume buoyancy by the atmosphere. However, the plume axis may still be rising or falling in this region, and it is instructive to compare measured plume rise values at these intermediate downwind distances with the levelling-off values predicted in the literature. For convenience the term plume rise will be applied to all data discussed in this paper even though it may be beyond the levelling-off point.

The levelling-off point in neutral conditions occurs at some downwind distance usually designated by the number of stack heights from the emission source. This results in the following modification to equation 2:

$$\frac{\overline{\Delta Z}}{L} = K \left(\frac{nh}{L} \right)^{2/3} \qquad (3)$$

where $\overline{\Delta Z}$ is the final plume rise and h is the stack height. Briggs, in a simple analysis predicts a levelling-off at $n = 10$.

On the other hand Moore (1974) postulates a 3/4 power law dependence with downwind distance of the form

$$\Delta Z = K \frac{F^{1/4} X^{3/4}}{U} \tag{4}$$

in which X tends to a limiting value of about 1 km in unstable or neutral conditions. This would correspond to X = 15 h in the current analysis. (Equation 3)

For stable conditions, equation 1 is valid up to $X = 2.4\ US^{-\frac{1}{2}}$. Beyond this downwind distance, according to Briggs, the final plume rise is defined as:

$$\overline{\Delta Z} = 2.9 \left(\frac{F}{US}\right)^{1/3} \tag{5}$$

$\sqrt{S}$ corresponds to the stability term known as the Brunt-Vaisala frequency. Moore sets his limiting plume rise in stable conditions according to Equation 4 but with X constant at a value of a few hundred metres.

In previous publications the authors have shown that the above relationships give useful and valid interpretations of measured plume rise data (see Whaley (1974, 1976, 1977, 1978, 1980)). However, these data indicated that parameters other than the Briggs stability parameters are required to interpret more fully the data for plume rise in stable conditions. The parameter used in this paper is a modified form of the bulk Richardson number suggested by Hanna et al (1977) Draxler (1976) and Munn (1970).

where $$R_b = \frac{g\, Z_p^{\,2}}{4\bar{U}^{\,2} T} \left(\frac{\partial \Theta}{\partial Z}\right) \tag{6}$$

From an examination of Equation 5 it is clear that the bulk Richardson number will increase as stability increases and that the dry adiabatic lapse rate correponds to $R_b = 0$. Unstable conditions correspond to negative values of Rb and the authors have categorized positive values of Rb coupled with potential temperatured gradients above isothermal conditons as stable ($\partial\Theta/\partial Z > 0.5$).

2.4. Plume spread parameters

Whaley et al (1974, 1976, 1977, 1978, 1980) have shown that the Pasquill-Gifford relationships give useful comparisons with measured plume spread data. However, these data indicated that parameters other than the Pasquill stability classes might be required to interpret more fully the data for plume spread, particularly in stable conditions.

Since the bulk Richardson number appeared to offer some quantification of stability, it was decided to use it as well as the Pasquill classes to correlate plume standard deviations. The Pasquill stability classes used in this paper were selected on the basis of the following potential temperature ranges:

PASQUILL STABILITY	CLASSIFICATION	$\partial\Theta/\partial Z$ °C/hm
C	Slightly unstable	-1.5 to -0.5
D	Neutral	-0.5 to +0.5
E	Moderately stable (isothermal)	0.5 to 1.5
F	Stable	>1.5

A negative value of the bulk Richardson number, R_b, corresponds to the unstable classification on Pasquill C but positive values can be neutral or more stable, Pasquill D,E, and F. In the studies described here, 5 Pasquill D class studies and 4 F class studies had values of $R_b>2$. The R_b ranges chosen to rank the data were as follows: R_b negative, $0<R_b<2$, $R_b>2$, since statistical examination of the data had indicated that this was the maximum number of ranges which would ensure adequate numbers of data points in each category.

3. DISCUSSION OF MEASURED PLUME DISPERSION DATA

3.1. Plume rise, neutral conditions

Previous papers by the authors have utilized the Briggs relationship for neutral plume-rise evaluations. In these papers, which represent individual case studies mentioned in Table 1, the 2/3 power law dependence of the plume rise data with downwind distance is endorsed; however, the value of the proportionality constant is usually lower than the 1.6 noted by Briggs. Figure 1a is a plot of the CCRL data for the buoyant plume-rise region and the following equation is based on a 2/3 power law constrained regression analysis of the data

$$\frac{\overline{\Delta Z}}{L} = 0.87 \left(\frac{X}{L}\right)^{2/3} \tag{7}$$

where X<15 h. An examination of these data show that levelling-off occured at X = 15 h rather than at X = 10 h as suggested by Briggs; in addition the regression constant of 0.87 is much lower than the Briggs widely accepted value of 1.6. It was felt that the regression analysis should be constrained otherwise the inverse relationship of plume rise with wind speed would be altered. The true regression analysis is as follows:

$$\frac{\overline{\Delta Z}}{L} = 0.54 \left(\frac{X}{L}\right)^{0.71} \tag{8}$$

which had a standard error of 2.36 and a correlation coefficient of 0.9. The power relationship given Equation 8 is between those of Briggs and Moore but both of these latter relationships tend to overestimate the data as shown in Figure 1a. This is probably partly due to the range of source types studied from low momentum, high buoyancy refinery stacks to high momentum low buoyancy smelter stacks and to the different methodologies employed in acquiring and reducing the measured data. Figure 1b shows the plume-rise data at X>15 h correlated with the predicted levelling-off values from Equation 7, and the correspondance is seen to be excellent.

3.2. Plume rise, stable conditions

It has already been noted that stable plumes have a tendency to level-off and then return back to the emission level at large downwind distances as the plume buoyancy is assimulated by the atmosphere. Figure 2a shows the variation of the limiting plume rise with downwind distance under stable conditions. In this plot, excellent agreement with Briggs' limiting value of $\overline{\Delta Z}\ (US/F)^{1/3} = 2.9$ can be observed, with only a slight decrease with increasing distance. However, the limiting downwind distance was at $XS^{1/2}/\overline{U} = 18.4$ rather than at 2.4 as predicted by Briggs. The standard error was 0.32.

The correlation of the limiting plume rise with bulk Richardson number is shown in Figure 2b and can be represented by the relationship:

$$\overline{\Delta Z}\ (US/F)^{1/3} = 2.61\ R_b^{\ 0.11} \tag{9}$$

with a standard error of 1.43.

3.3. Plume spread, Pasquill C/D

It has been previously stated by the authors that horizontal plume spread data obtained in neutral or unstable conditions is usually wider than the Pasquill stability class would suggest. In this case a single plot of C and D class stability data shown in Figure 3a revealed a correlation corresponding to between A and B or two classes wider than expected.

In the vertical dimension the data agreed with the P/G curves for C and D respectively (Figures 3b and c) at between 4 to 10 km from the source. Further from the sources the P/G curves overestimated and closer they underestimated the measured data. The following correlations were found:

C Class $\sigma_z = 130\ X^{0.204}$ (10) $\sigma_y = 195\ X^{0.752}$ (12)
D Class $\sigma_z = 93\ X^{0.204}$ (11)

3.4. Plume spread, Pasquill E/F

The horizontal spread of stable plumes is much wider than would be predicted by the corresponding P/G curves as was the case with unstable or neutral plumes. For E class stability, the spread is two classes wider i.e. C stability (Figure 4a) and for F class stability six classes wider (Figure 5a) i.e. A stability.

Again the vertical spread is in agreement with the P/G curves at about 7 to 9 km from the source (Figures 4b and 5b). The measured values are underestimated closer to the source and overestimated further away. The following relationships were found:

E Class $\sigma_z = 44 \text{ X}^{0.204}$ (13) $\sigma_y = 142 \text{ X}^{0.752}$ (15)

F Class $\sigma_z = 26 \text{ X}^{0.204}$ (14) $\sigma_y = 256 \text{ X}^{0.752}$ (16)

3.5. Plume spread, Bulk Richardon Number

When the data for plume spread were correlated for three ranges of Rb, negative 0 to 2, and greater than 2 (Figure 6), it was found that all the horizontal data could be represented by the relationship:

$$\sigma_y = 192 \text{ X}^{0.752} \quad (17)$$

There was no apparent difference in the horizontal data when grouped according to the three ranges of R_b. Vertical spread, σz could be correlated as follows:

$R_b<0$, $\sigma_z = 151 \text{ X}^{0.173}$ (18)

$0<R_b<2$, $\sigma_z = 70 \text{ X}^{0.173}$ (19)

$R_b>2$, $\sigma_z = 56 \text{ X}^{0.173}$ (20)

4. CONCLUSIONS

Measured plume dispersion parameters obtained in six geographic regions of Canada have been correlated according to the stability classes of Pasquill and also by the bulk Richardson number.

1) Measured plume rise values have shown good agreement with the relationships suggested by Briggs for both neutral and stable conditions and by Moore for neutral conditions.

2) The Briggs and Moore equations for plume rise in neutral conditions in general overestimated the CCRL data by about 85%. This discrepancy is probably due in part to the range of sources studied and the different methods of determining the plume rise parameters. The CCRL data had a 0.71 power law dependence with downwind distance which fell between the two relationships of Briggs and Moore. It was also found that plumes tend to level-off at X = 15 h rather than at X = 10 h as suggested by Briggs.

3) The Briggs equation for stable conditions gave an excellent prediction of the final rise of the plumes, but in general this occurred at a dimensionless distance of 18.4 rather than at 2.4. It was found that the final plume rise could be correlated with the bulk Richardson number in the form of a 0.11 power law relationship. In stable conditions the bulk Richardson number, developed in the paper, appears to provide a more definitive classification than either S as defined by Briggs or classifications E and F as defined by Pasquill, for assessing the maximum buoyant plume rise.

4) It was found that the P/G curves always underestimated σ_y by at least two classes for unstable neutral and moderately stable; in the case of stable conditions (Class F) the data was six classes (Class A) wider than expected.

   Horizontal σ_y data could be represented as follows:

   C/D Classes , $\sigma_y = 195\ X^{0.742}$

E Class , $\sigma_y = 142\ X^{0.752}$

F Class , $\sigma_y = 256\ X^{0.752}$

5) Vertical spread σ_z was generally in agreement with the P/G curves at between 4 and 10 km from the source. Closer to the source the measured values were underestimated and farther away, overestimated. Vertical σ_z data could be represented as follows:

C Class , $\sigma_z = 130\ X^{0.204}$

D Class , $\sigma_z = 93\ X^{0.204}$

E Class , $\sigma_z = 44\ X^{0.204}$

F Class , $\sigma_z = 26\ X^{0.204}$

6) The bulk Richardson number, R_b, did not provide the degree of resolution for ranking plume spread data as did the Pasquill stability classes. There was no significant difference between the horizontal spread data which could be represented by:

$$\sigma_y = 192\ X^{0.752} \quad \text{(all values of } R_b\text{)}$$

Vertical spread could be correlated by:

$R_b<0$, $\sigma_z = 151\ X^{0.173}$

$0<R_b<2$, $\sigma_z = 70\ X^{0.173}$

$R_b>2$, $\sigma_z = 56\ X^{0.173}$

7) Six years of plume dispersion research in Canada have shown that measured plume rise and spread data can differ significantly from the established predictive methods in the literature.

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TABLE 1 - EMISSION SOURCE DATA FROM THE CCRL PLUME RESEARCH PROGRAM

Source Type	Geographic Conditions*	Stack Heights, m		Total SO_2 Emission kg/s**	Total Heat Emission MJ/s
Coal-Fired	2,U	1	152		
Power Station	F,S	2	152	5.0	220
		3	152		
		4	152		
Smelter	1,R	1	152		
	F	2	152	50.0	936
		3	106		
Coal-Fired	1,R	1	92		
Power Station	F,W	2	92	0.6	120
		3	56		
Refinery	4,A	1	106		
	F,W	2	106	1.9	104 W
		3	106	6.5	78 F
		4	76		
Sour Gas	3,R	1	152		
Plant				2.7	125
	S			1.2**	118**
Sour Gas	3,R	1	107	0.2	21
Plant				0.3**	5.2**
Smelter	4,R	1	122	0.8	25
	S	2	122		
		3	87		

TABLE 1 - CONT'D

Sour Gas Plant	3,R S	1	135	1.8 23.0**	125 1250**
Sour Gas Plant	3,R S	1	98	0.5	12.6
Sour Gas Plant	3,R S	1	61	1.0	21.2

*Legend

1. Flat terrain.
2. Land adjacent to large bodies of water.
3. Rolling terrain or foothills.
4. Shallow or deep river, mountain valleys.

U = Urban
R = Rural
A = Sub-arctic

F = Fall
W = Winter
S = Spring

**Repeat study, same season at same plant.

Fig. 1 - Dimensionless plume rise correlations, neutral conditions

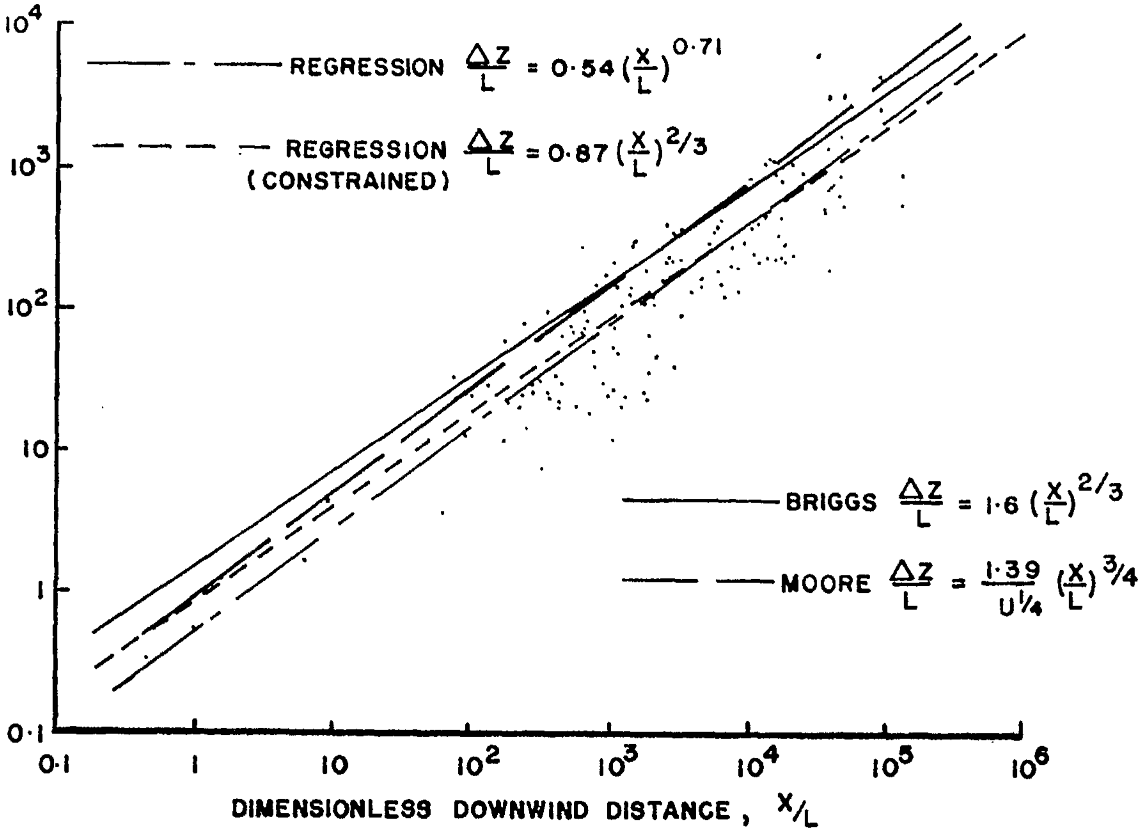
Fig. 2 - Variation of dimensionless plume rise with dimensionless
downward distance and bulk Richardson number, stable conditions

Fig. 3 - Plots of plume standard deviations for unstable/neutral
P/G Classes C and D

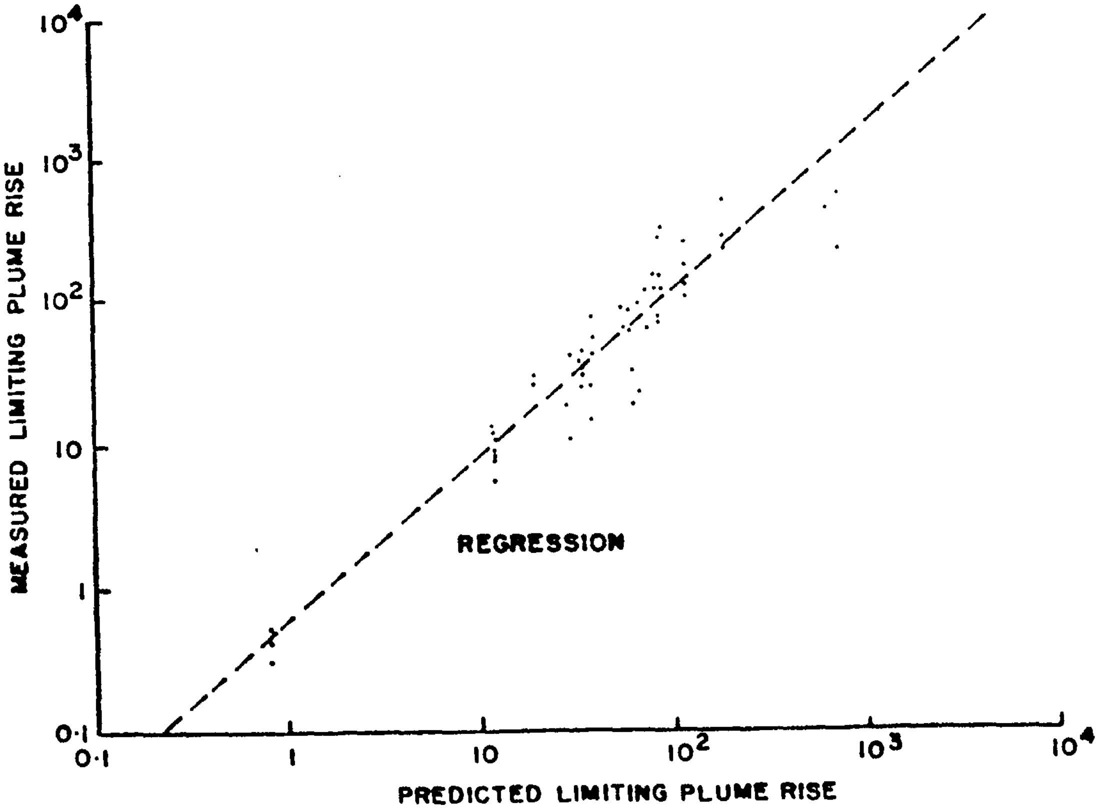
Fig. 4 - Plots of plume standard deviations for stable conditions,
P/G Class E

Fig. 5 - Plots of plume standard deviations for very stable
conditions P/G Class F

Fig. 6 - Variation of plume standard deviations with
bulk Richardson number

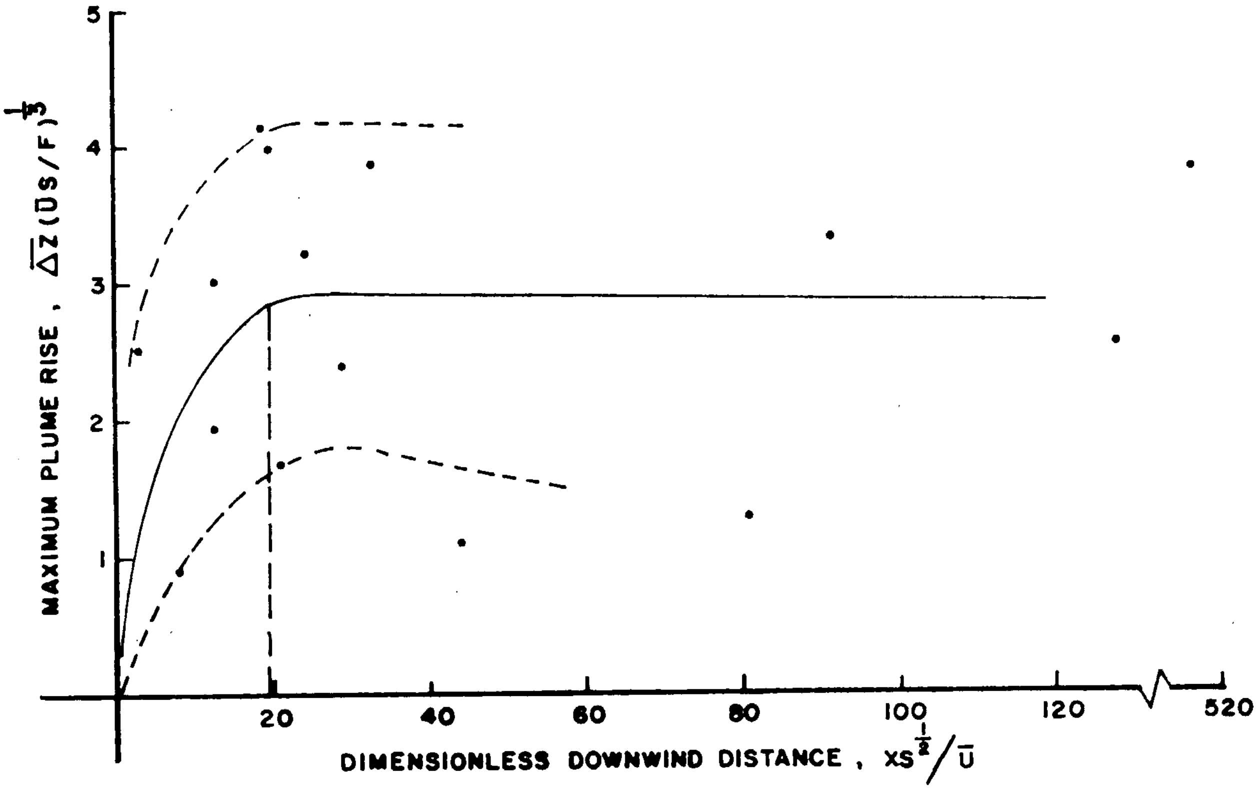


a) Buoyant plume rise region

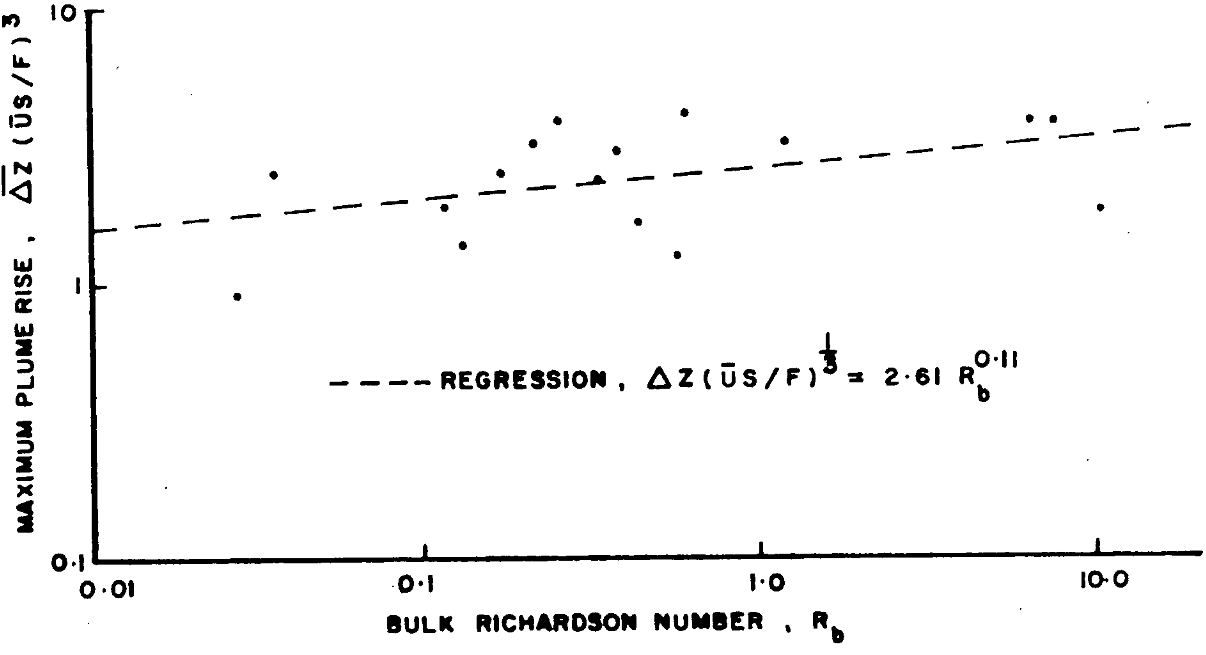


b) Levelling-off region, x>15 h

Fig. 1 - Dimensionless plume rise correlations, neutral conditions

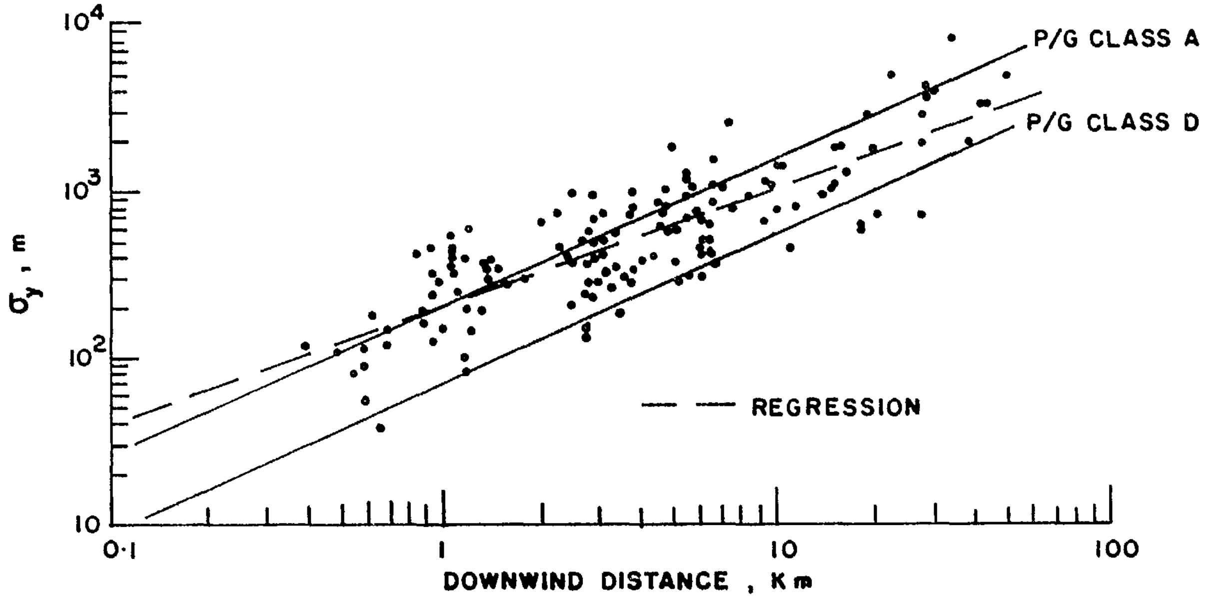


a). Variation of limiting rise with downward distance

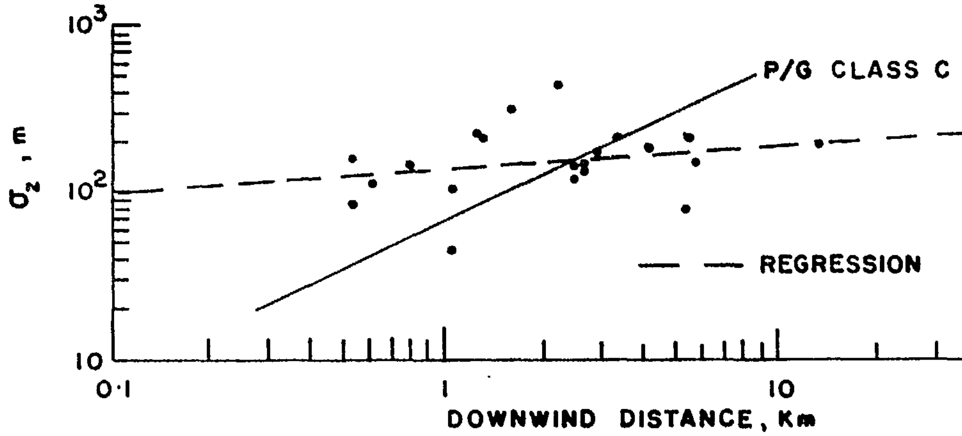


b) Variation of limiting rise with bulk Richardson number

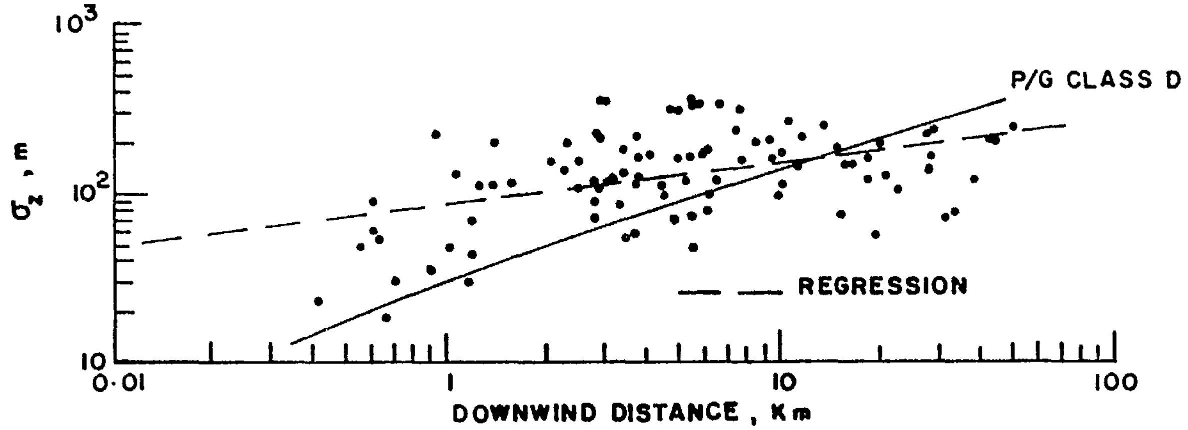
Fig. 2 - Variation of dimensionless plume rise with dimensionless downward distance and bulk Richardson number, stable conditions



a) σy, unstable/neutral P/G C and D

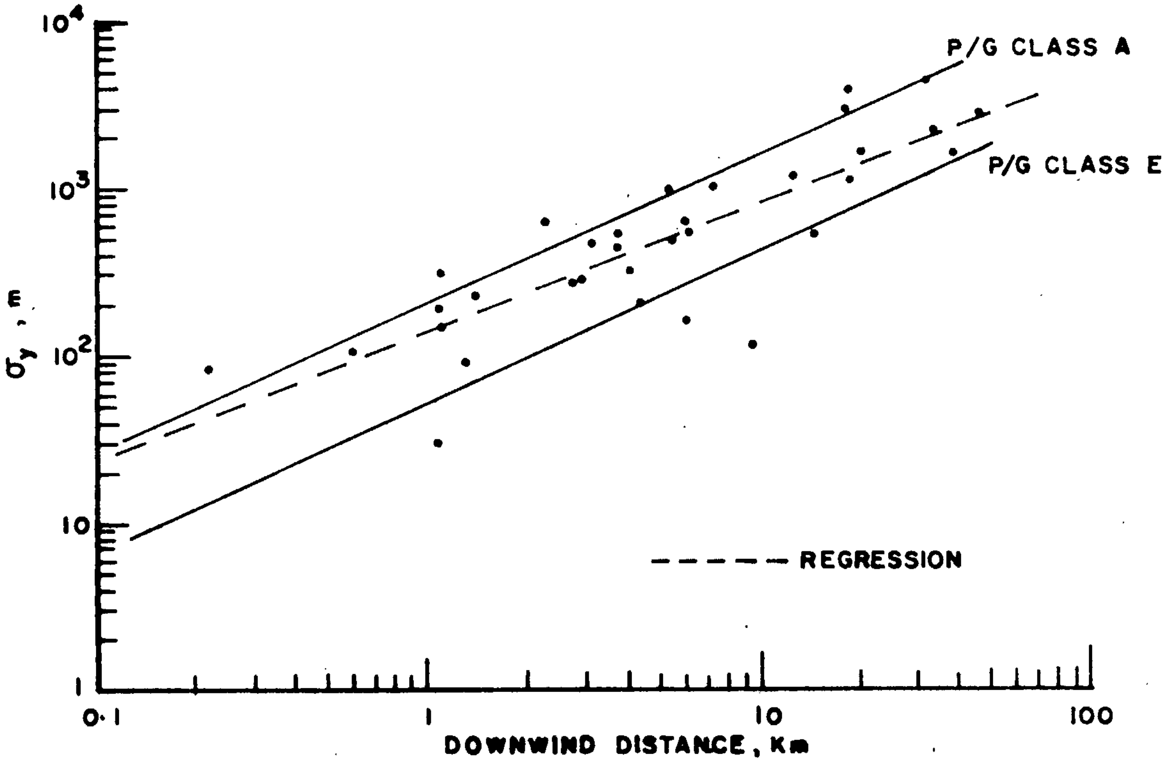


b) σz, unstable P/G Class C

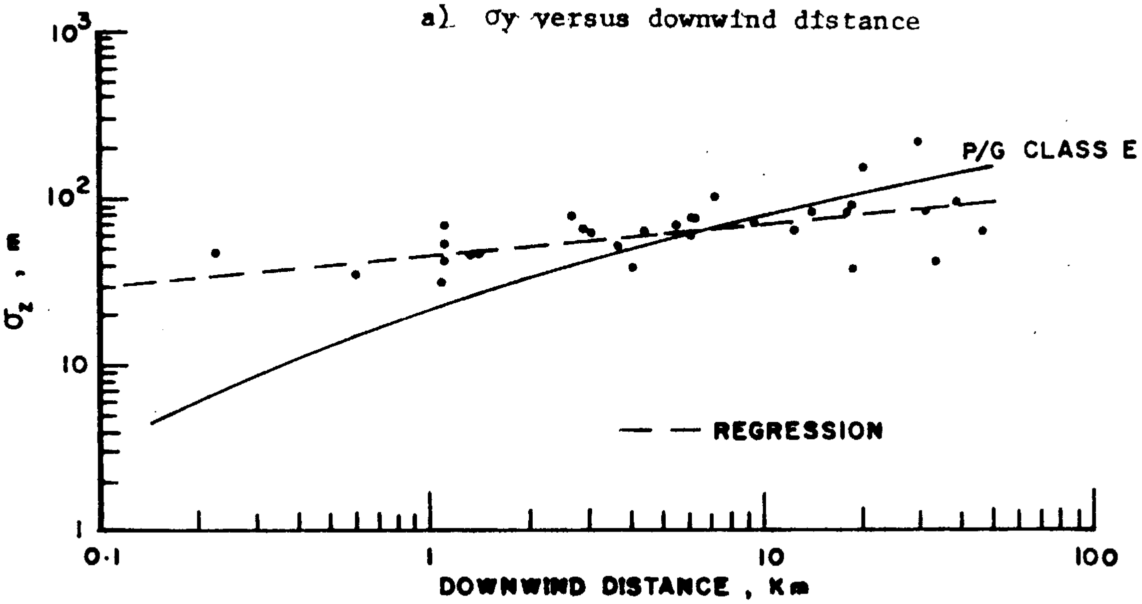


c) σz, neutral P/G Class D

Fig. 3 - Plots of plume standard deviations for unstable/ neutral P/G Classes C and D

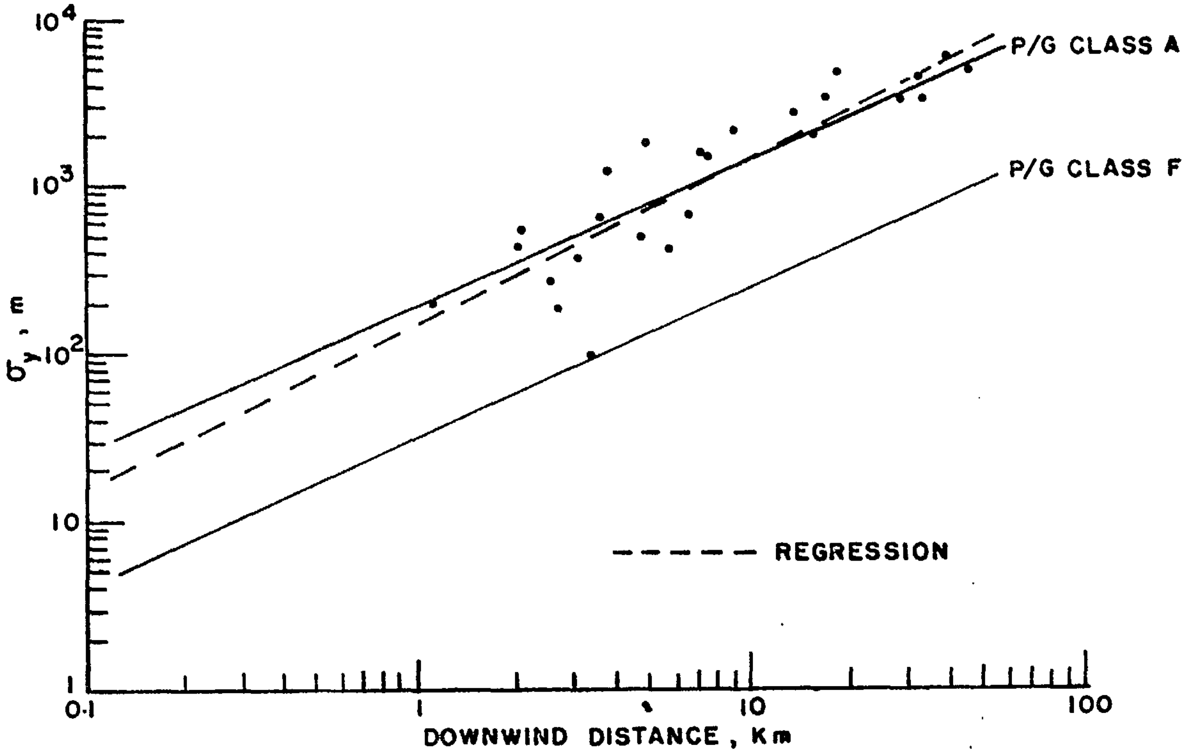


a) σy versus downwind distance

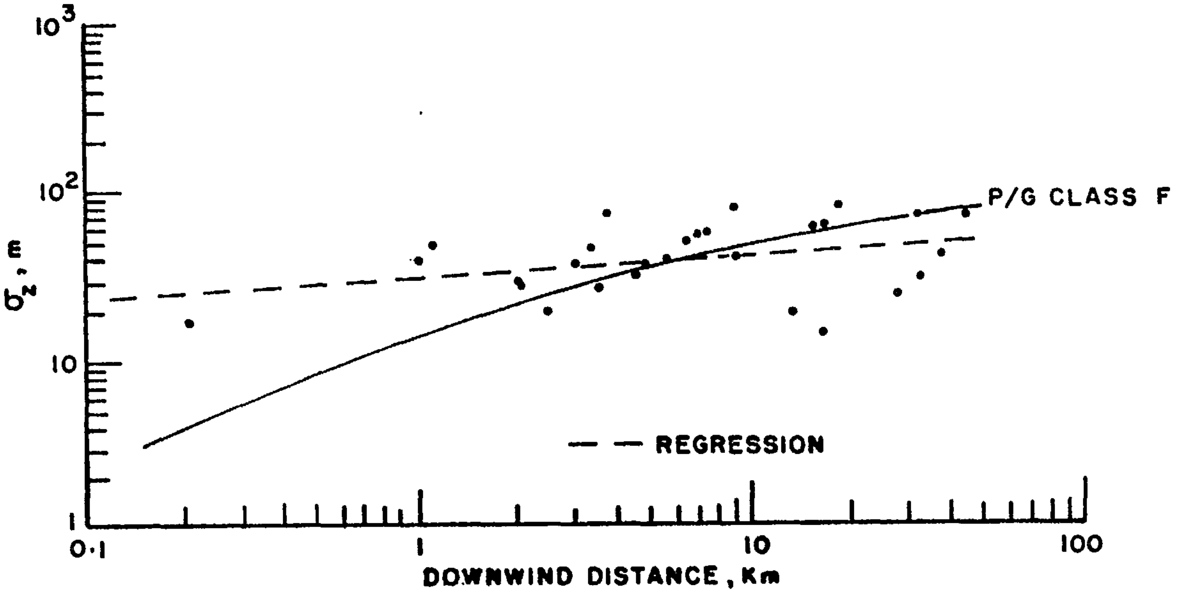


b) σz versus downwind distance

Fig. 4 - Plots of plume standard deviations for stable conditions, P/G Class E

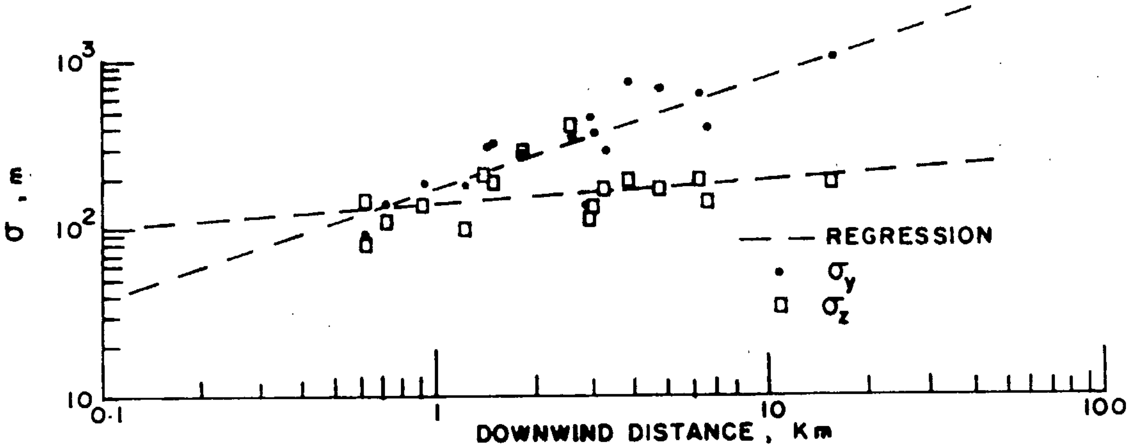


a) σy versus downwind distance

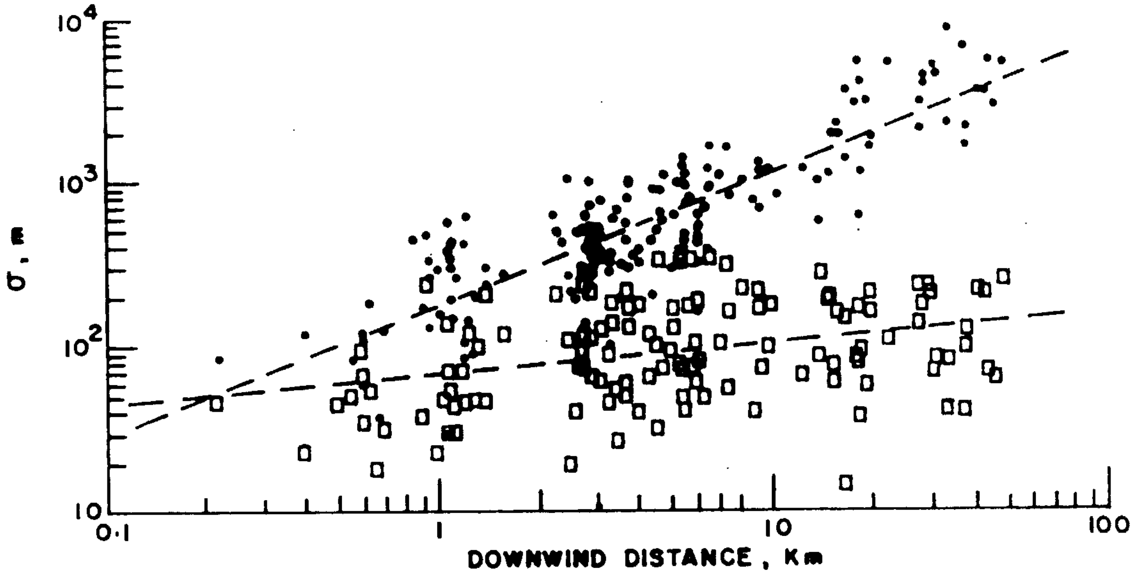


b) σz versus downwind distance

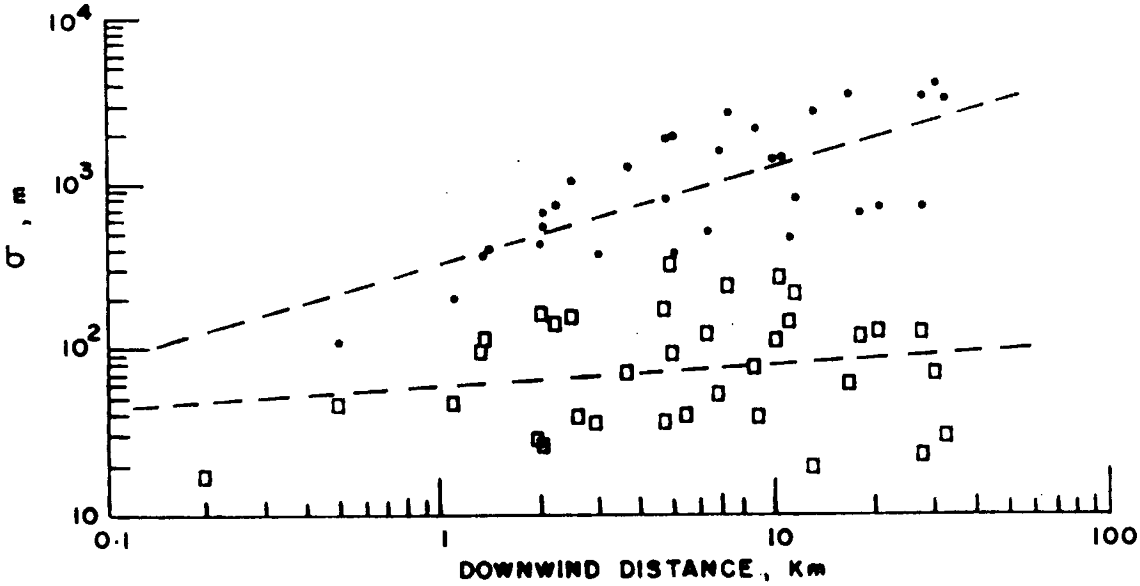
Fig. 5 – Plots of plume standard deviations for very stable conditions P/G Class F



a) $Rb<0$



b) $0<Rb<2$



c) $Rb>2$

Fig. 6 - Variation of plume standard deviations with bulk Richardson number