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DISPERSION PARAMETERS MEASURED DURING NEUTRAL AND STABLE CONDITIONS IN CANADA

By

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

Abstract

Plume spread 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 Pasquill and 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.

The Pasquill-Gifford 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

g	=	gravitational constant, m/s^2
R_b	=	bulk Richardson number = $\frac{gZ_p^2}{4\bar{U}^2T} \quad \frac{\partial\Theta}{\partial Z}$
S	=	stability parameter = $(g/T)\ (\partial\Theta/\partial Z)$, 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
Z_p	=	height of plume top above terrain, m
$\frac{\partial\Theta}{\partial Z}$	=	vertical potential temperature gradient, °C/m
σ_y, σ_z	=	horizontal and vertical standard deviations respectively, m

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.

The CCRL Plume Dispersion Research Program

Background

In 1969 it was clear that reliable information on dispersion parameters was not available in Canada [(1)]. 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 characterized by:

(1) Flat terrain.
(2) Land adjacent to large bodies of water.
(3) Rolling terrain or mountain foothills.
(4) Deep mountain valleys and river valleys.
(5) Arctic and sub-arctic regions.

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 elsewhere [2].

The program was jointly sponsored with industry and meteorological support was provided by Atmospheric Environment Services (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.

The Derivation of Plume Spread Parameters

The CCRL Program

In the CCRL program, it has been found that the voluminous data obtained by aerial probing techniques can best be evaluated numerically by a three-step procedure which employs the method of finite differences (2). This method, which is mathematically rigorous, eliminates any discrepancies introduced by a subjective approach and minimizes errors due to acquiring data by instruments that have short response times.

The first step in the method involves the reconstruction of three or more cross-wind sections of the plume to show spatial concentration isopleths that are plotted from continuous SO_2 measurements along accurately located cross-wind traverse lines in space. The second step consists of digitizing the spatial co-ordinates of each SO_2 contour of the plume cross-section to establish the co-ordinates of the centre of pollutant mass flow, and the standard deviations σ_y and σ_z. The data can then be used to reconstruct plan and side views of the plume on which the centre of pollutant mass can be accurately located. Downwind distance and plume rise are determined from these plots which show the horizontal and vertical variation of the plume axis with downwind distance.

In simple dispersion models the plume axis is usually a horizontal line in the mean wind direction at the effective height of emission, plume rise plus stack height. It is from this elevated location that the vertical and horizontal process of dispersion is assumed to begin. In a more complex model detailed measurements of the spatial variation of wind and temperature together with topographical information may be used to predict more closely the complex variation in the plume behaviour that may occur in practice.

Most dispersion models, being derived from statistical or physical principles, are gaussian in nature. In such a model the gases emitted from a stack become distributed across the plume in a gaussian or normal distribution. Thus, in three-dimensions, if axial diffusion is neglected, the model represents a bivariate normal distribution in the plane normal to the plume axis. A gaussian distribution may be completely defined by its standard deviation if represented in dimensionless form. Therefore, in the bivariate three-dimensional model, the horizontal and vertical standard deviations σ_y and σ_z, respectively have been used to report plume dispersion spread parameters in the literature.

The importance of accurate 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 influence ground-level impingement concentrations. Pioneers of the concept of using standard deviations of plume spread were Pasquill (3,4) who used angular values, and Gifford (5) who converted these to linear dimensions and developed the well known graphical representations. A later representation by Bowne (6) who developed the Pasquill-Gifford, (P/G) σ_y and σ_z curves for rural conditions, was used for comparative purposes in this paper.

Neutral and Stable Plume Stability Parameters

In previous publications (7-12) the authors have shown that the above relationships give useful and valid comparisons of 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. The parameter used in this paper is a modified form of the bulk Richardson number suggested in the literature (13,14,15) and used by the authors to correlate plume rise in stable conditions (16).

$$R_b = \frac{g\, Z_p^2}{4\bar{U}^2 T} \quad \frac{\partial \Theta}{\partial Z}$$

From an examination of the above relationship it may be noted that the bulk Richardson number will increase as stability increases and that the dry adiabatic lapse rate correponds to $R_b = 0$. Unstable conditions represent $R_b<0$ and the authors have categorized $R_b>0$ combined with potential temperature gradients higher than isothermal (>5°C/km) as stable. It is clear that the bulk Richardson number is a more comprehensive form of that developed by Briggs (17)

$$S = \frac{g}{T} \quad \frac{\partial \Theta}{\partial T}$$

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 numbers, 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, $0>R_b>2$, $R_b<2$. As 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.

Discussion of Measured Plume Spread Data

Unstable and Neutral Conditions, Pasquill C and D

It has been previously stated by the authors (6-11) 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 1 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 2 and 3) 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 $\sigma_z = 130\ x^{0.204}$ $\qquad$ $\sigma_y = 195\ x^{0.752}$

D Class $\sigma_z = 93\ x^{0.204}$

Stable Conditions, Pasquill E and 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 4) and for F class stability six classes wider (Figure 5) 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 6 and 7). The measured values are underestimated closer to the source and overestimated further away. The following relationships were found:

E Class	$\sigma_z = 44\ x^{0.204}$	$\sigma_y = 142\ x^{0.752}$
F Class	$\sigma_z = 26\ x^{0.204}$	$\sigma_y = 256\ x^{0.752}$

Bulk Richardson Number

When the data for plume spread were correlated for three ranges of Rb, negative (Figure 8) 0 to 2 (Figure 9) and greater than 2 (Figure 10) it was found that all the horizontal data could be represented by the relationship:

$$\sigma_y = 192\ x^{0.752}$$

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:

$R_b<0$,	$\sigma_z = 151^{0.173}$	(Figure 8)
$0<R_b<2$,	$\sigma_z = 70^{0.173}$	(Figure 9)
$R_b>2$,	$\sigma_z = 56^{0.173}$	(Figure 10)

Conclusions

Measured plume spread 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) 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	,	$\sigma_y = 256\ x^{0.752}$

2) 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	,	$\sigma_z = 26\ x^{0.204}$

3) The bulk Richardson number, R_b, did not provide the degree of resolution for ranking plume spread data as did the P/G 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:

$R_b<0$	,	$\sigma_z = 151\ x^{0.173}$
$0\leq R_b\leq 2$	,	$\sigma_z = 70\ x^{0.173}$
$R_b>2$	,	$\sigma_z = 56\ x^{0.173}$

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

List of Figure Captions

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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 Power Station	2,U F,S	1 152 2 152 3 152 4 152	5.0	220
Smelter	1,R F	1 152 2 152 3 106	50.0	936
Coal-Fired Power Station	1,R F,W	1 92 2 92 3 56	0.6	120
Refinery	4,A F,W	1 106 2 106 3 106 4 76	1.9 6.5	104 W 78 F
Sour Gas Plant	3,R S	1 152	2.7 1.2**	125 118**
Sour Gas Plant	3,R	1 107	0.2 0.3**	21 5.2**
Smelter	4,R S	1 122 2 122 3 87	0.8	25

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 F = Fall
R = Rural W = Winter
A = -Sub-arctic S = Spring

**Repeat study, same reason at same plant.

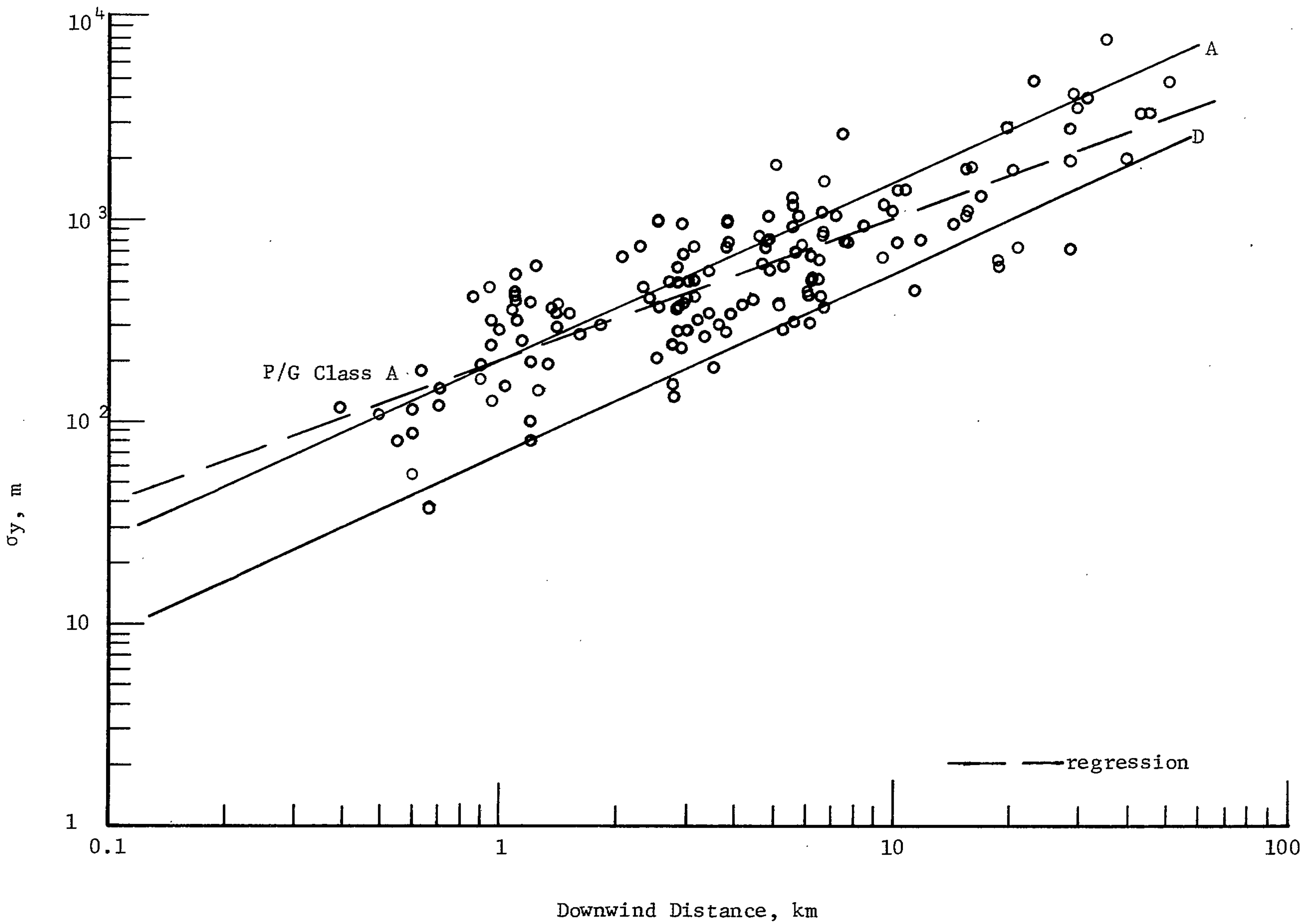


Fig. 1 - Plot of σy versus downwind distance for unstable/neutral conditions, P/G stability classes C and D

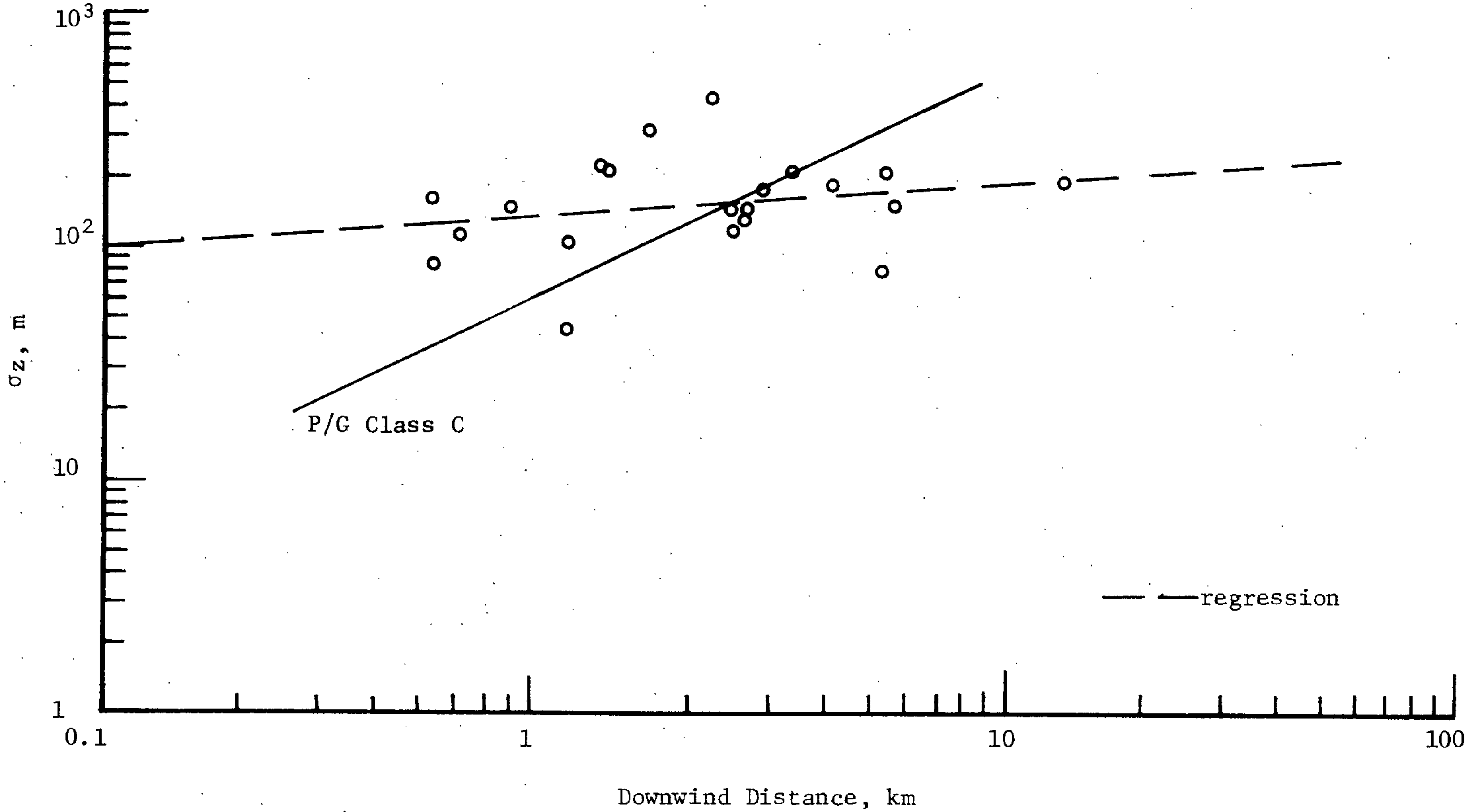


Fig. 2 - Plot of σz versus downwind distance for P/G stability Class C

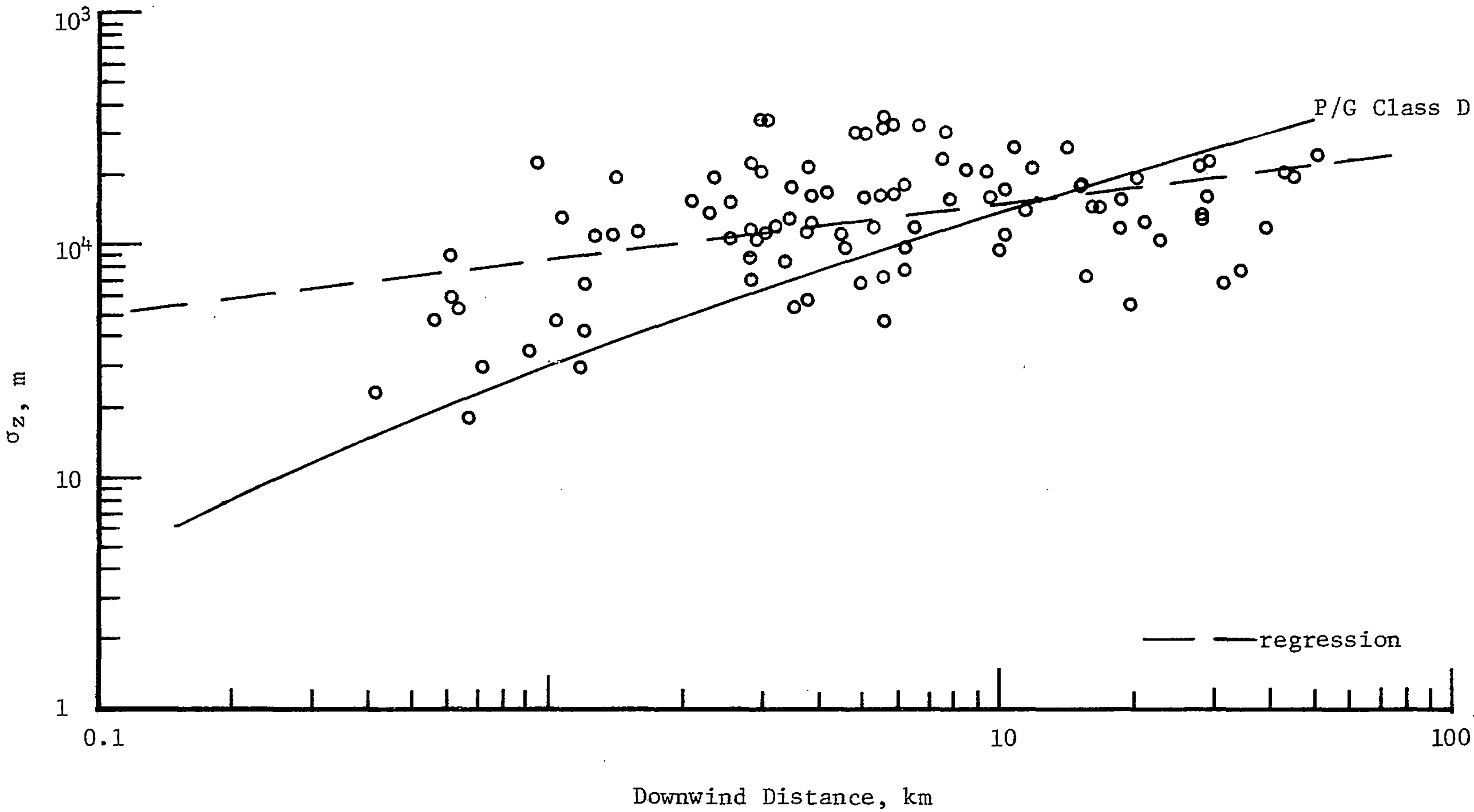


Fig. 3 - Plot of σz versus downwind distance for P/G stability Class D (neutral)

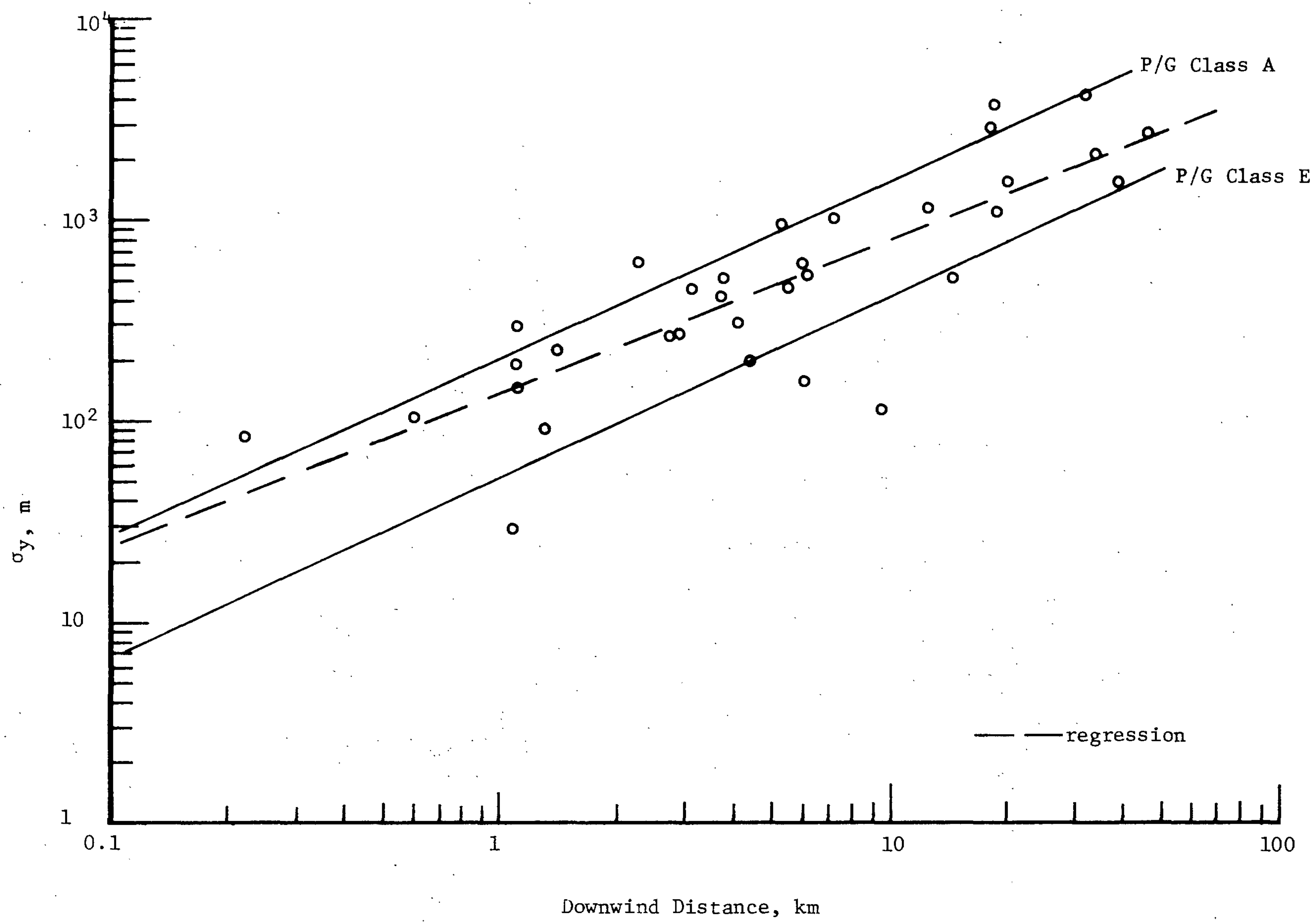


Fig. 4 - Plot of σy versus downwind distance for P/G stability Class E

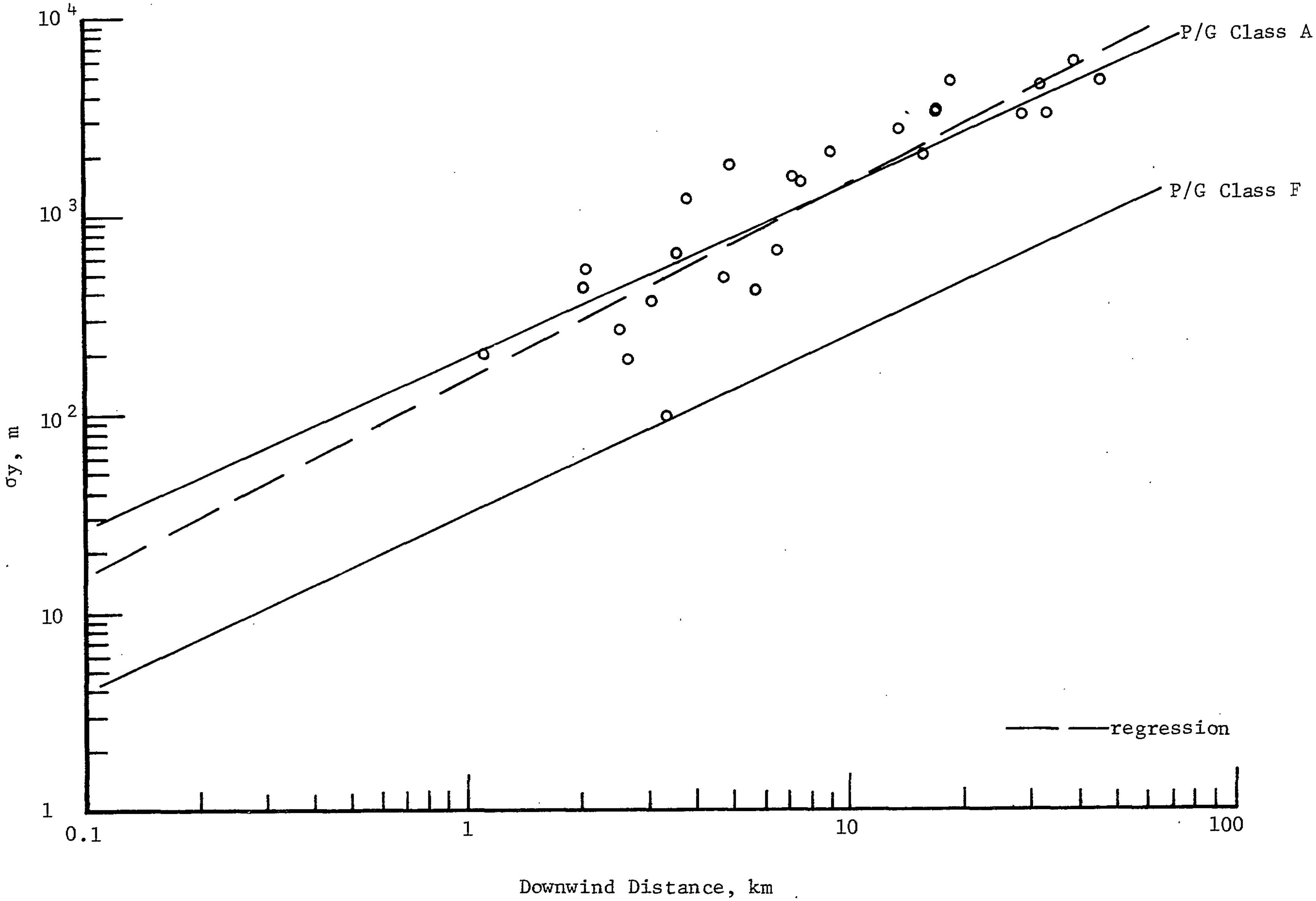


Fig. 5 - Plot of σ_y versus downwind distance for P/G stability Class F

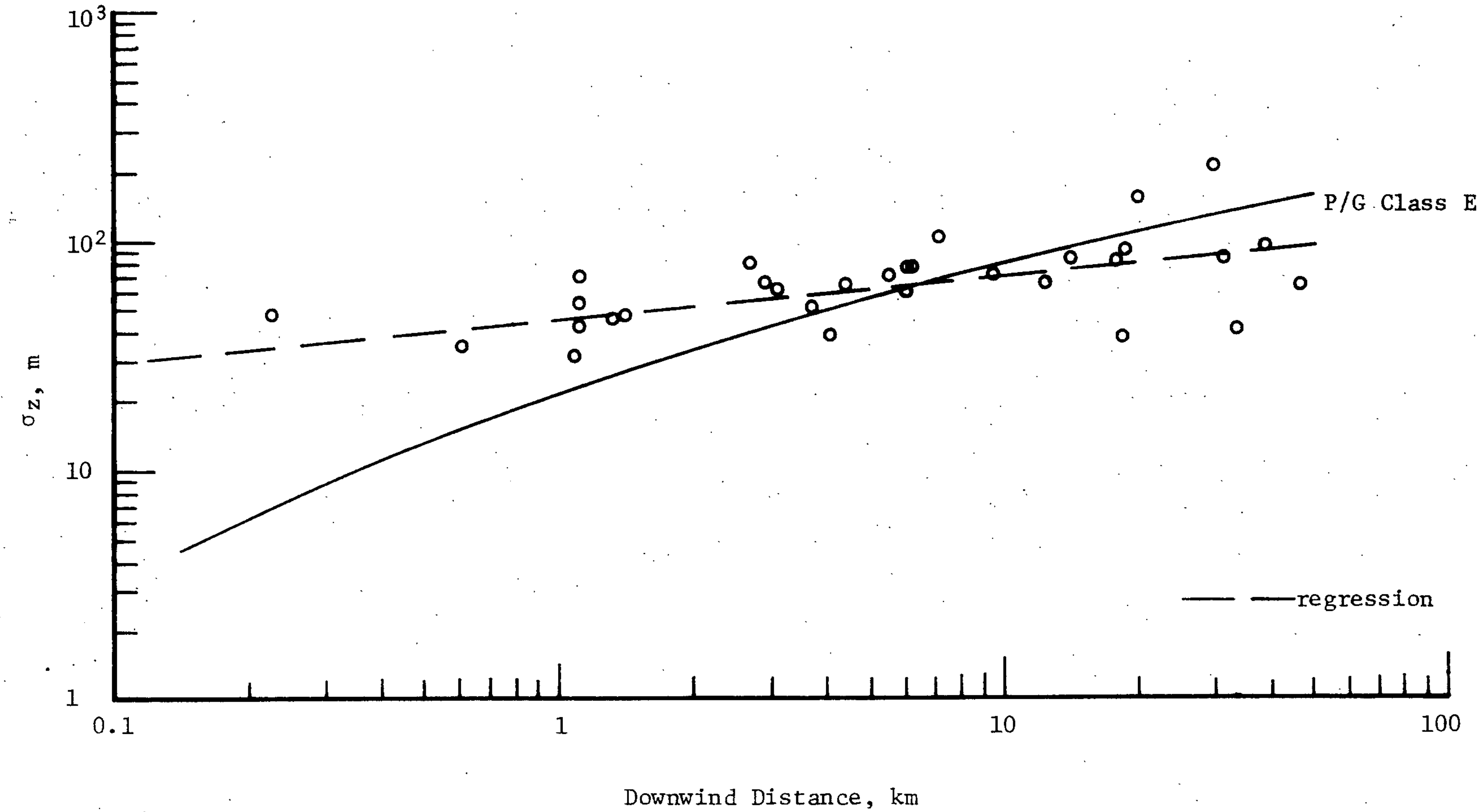


Fig. 6 - Plot of σ_z versus downwind distance for P/G Class E

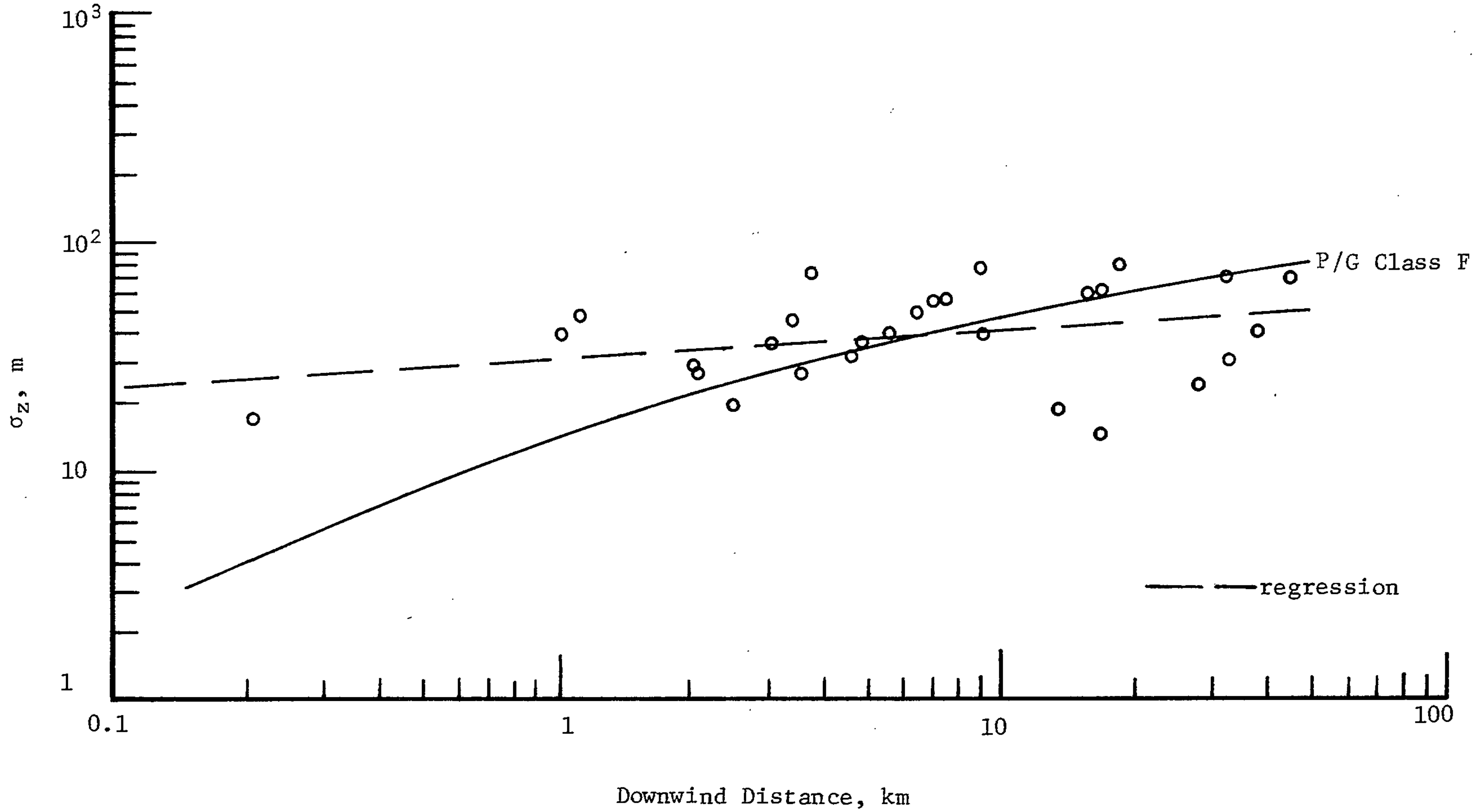
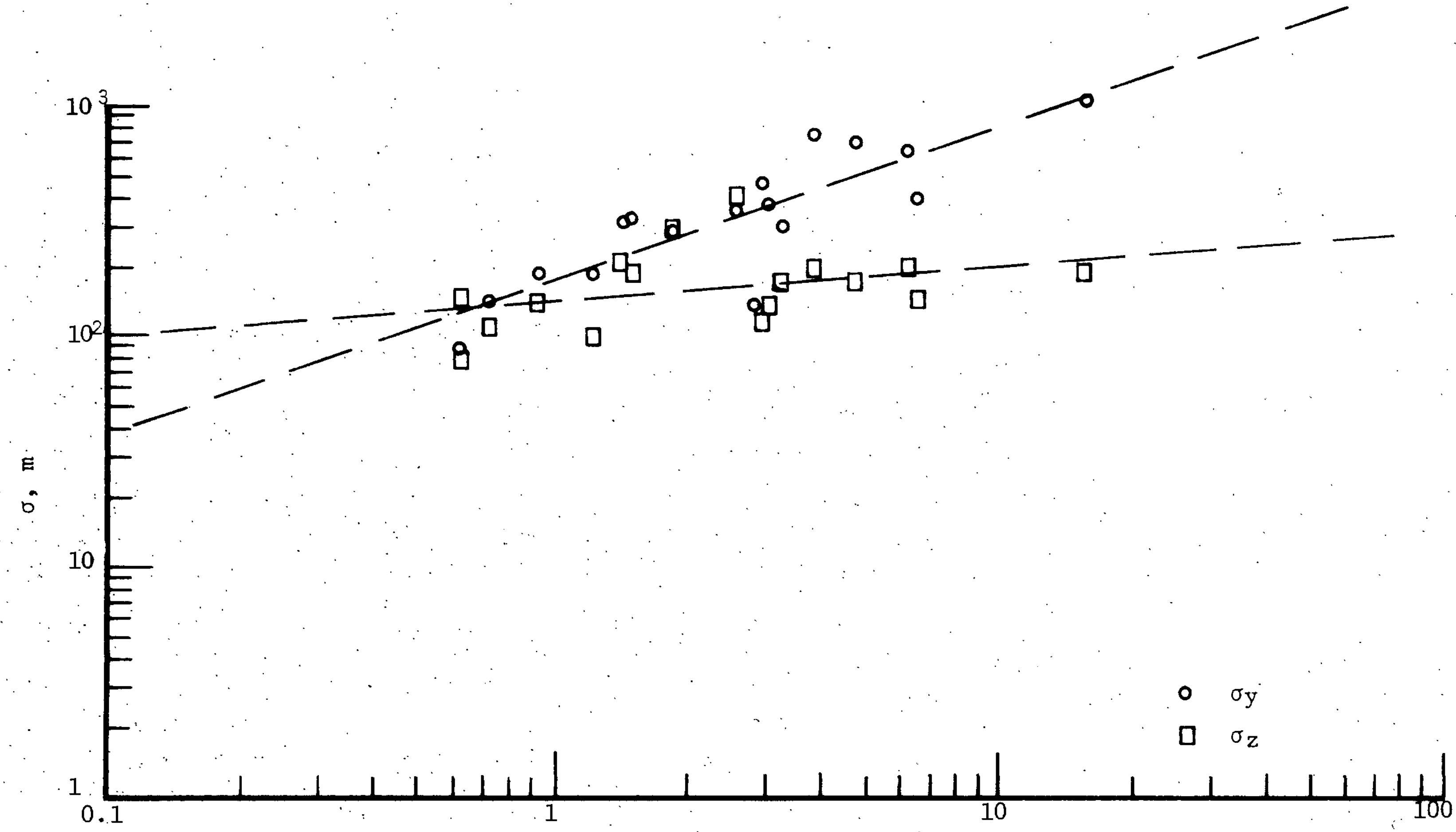


Fig. 7 - Plot of σz versus downwind distance for P/G stability Class F



Downwind Distance, km

Fig. 8 - Plots of σy, σz versus downwind distance for $R_b < 0$

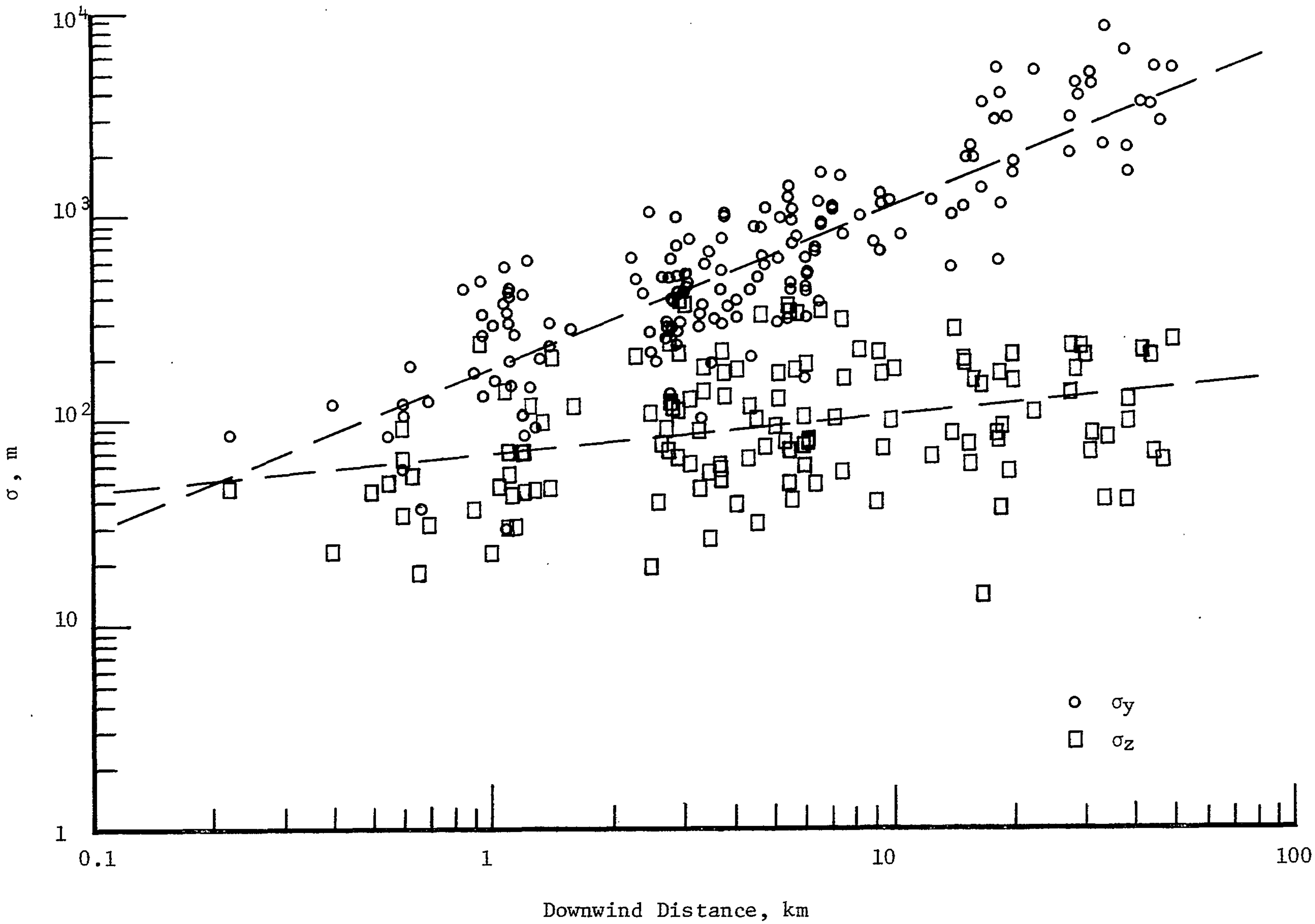


Fig. 9 - Plots of σ_y, σ_z versus downwind distance for $0 < R_b < 2$

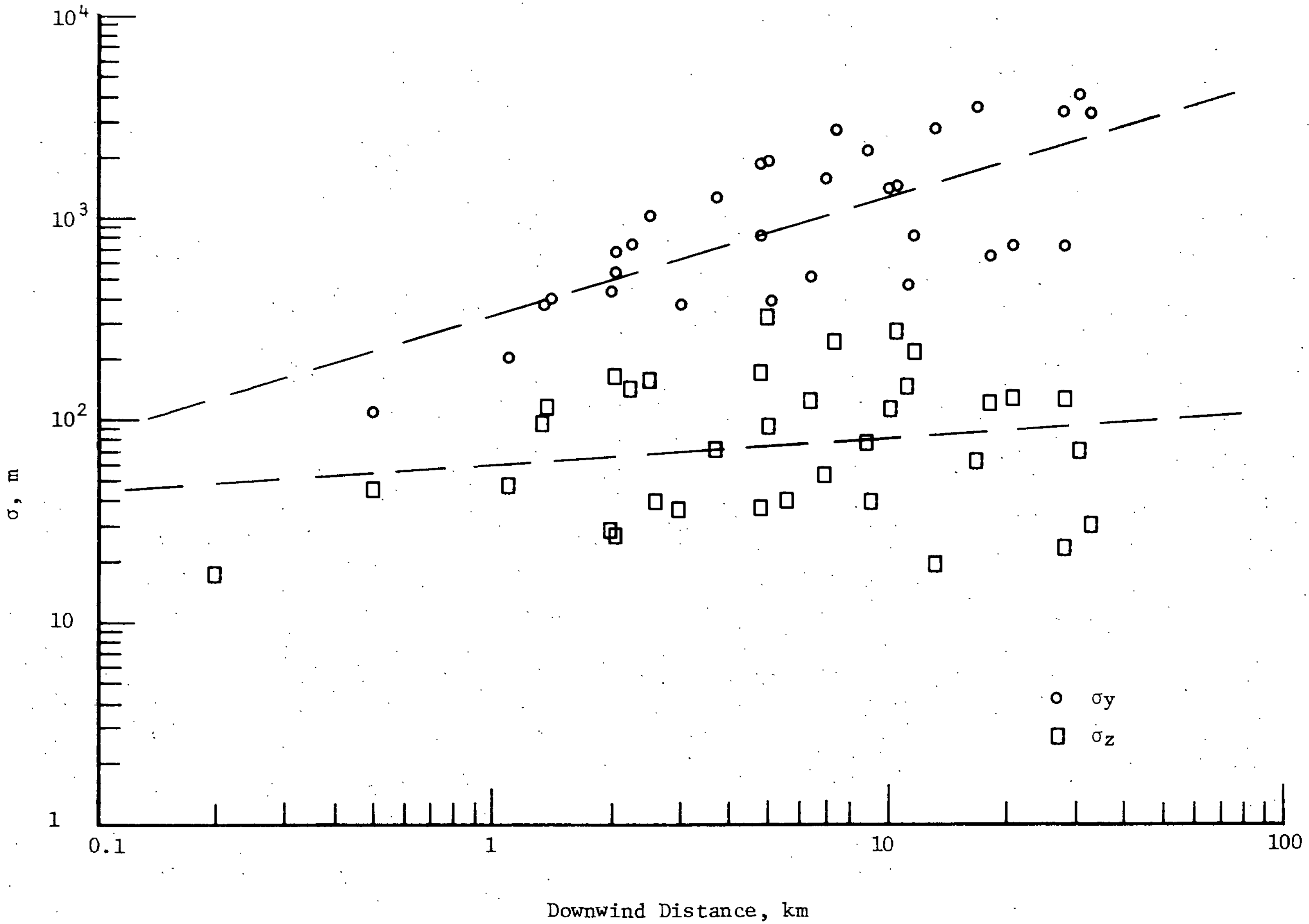


Fig. 10 - Plot of σy, σz versus downwind distance for R_b >2