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ATMOSPHERIC DIFFUSION: SIMILARITY THEORY AND EMPIRICAL DERIVATIONS FOR USE IN BOUNDARY LAYER DIFFUSION PROBLEMS

By

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Functional forms specifying the diffusion characteristics for turbulent flow in the atmosphere are developed, based on the similarity theory of the surface boundary layer. Descriptors of concentration and vertical spread for a continuous point source near the earth's surface are developed. Comparison to other treatises and to observational data both support the approach and confirm the accuracy of the method taken herein.

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CONTENTS

PARAMETER LIST

x,y,z are the parameters of a right-handed orthogonal system of coordinates with $+x$ in the downwind direction z to the zenith with the origin at the earth's surface.

$\overline{x},\overline{y},\overline{z}$ are mean coordinates of the center point of a diffusing cloud

t is time

a is a constant (about 1.25)

b is a constant (about 0.4)

h source or emission height (for Praire Grass data $\simeq$ 46 cm)

k is Von Karman's constant (about 0.4)

r is a parameter of the exponential power law

C is mass concentration (mass per unit volume)

L is the Monin-Obukhov length scale (see appendix)

Q is the source strength in units of mass per unit time

$\overline{u}$ is the mean windspeed

u_* is the friction speed

u', v', w', T' are instantaneous wind and temperature fluctuations

z_o is the surface roughness height (for Project Praire Grass about 0.7 cm)

α, δ, ε, η, μ, ω, Γ, dummy variables or arbitrary symbols

α is a constant (about 15)

$\zeta = z/L$

$\zeta_o = z_o/L$

$\overline{\zeta} = \overline{z}/L$

$\sigma_w = [\overline{w'w'}]^{\frac{1}{2}}$

$\sigma_\phi = \sigma_w/\overline{u}$

f, ϕ, are universal functions of the Similarity Theory

S is the normalized wind shear function

INTRODUCTION

This report describes the concepts of similarity theory applied to continuous source diffusion problems in the atmosphere.

Various papers have appeared expounding the use of similarity theory in diffusion methodology and estimation procedures. Gifford [1] described the similarity model for concentration at a downwind point due to a continuously emitting point source up to, but not including, a proportionality factor. His study indicated that the calculated power law index, m, of the inverse power law

$$\text{Concentration} \propto (\text{downwind distance})^{-m}$$

was in excellent agreement with data.

Klug [2] developed empirical functions which relate similarity theory to concentration data and found excellent agreement.

Pasquill [3] outlined several approaches used by others [1,4,5,] to describe the Lagrangian similarity approach to diffusion. His analysis indicates that the conventional similarity hypothesis fails to account for the effects of thermal stratification of the constant shearing stress layer in the atmosphere.

This report develops a proportionality in the concentration relation similar to that reported by Klug [2]. A vertical distribution function is selected for the falloff of concentration with height. By use of the vertical distribution, the vertical variance parameter is related to a similarity term, and estimates of cloud spread are given.

THEORY

Similarity Hypothesis for Turbulent Flow

The similarity hypothesis for turbulent flow in the constant stress layer or surface boundary layer of the atmosphere is that all statistical properties of the flow depend only on the ratio z/L [6]. For diffusion, the hypothesis is that the average vertical displacement, $\bar{z}$, of a cloud of passive material diffusing throughout the surface layer is uniquely determined by the friction velocity, $u_\star$, and a universal function $\phi(\bar{z}/L)$ [1,2,3].

This hypothesis is represented by the equation

$$\frac{d\bar{z}}{dt} = bu_\star\phi(\bar{\zeta}) \qquad (1)$$

where $\bar{\zeta} = \bar{z}/L$.

Assuming that the rate of increase of mean displacement, $\bar{x}$, of the particles of a diffusing cloud is equal to the average windspeed, $\bar{u}$, at the level $\bar{z}$ [3],

$$\frac{d\bar{x}}{dt} = \bar{u}(\bar{z}). \qquad (2)$$

The expression for downwind maximum concentration from a continuous point source located at the surface is given by the proportionality [1],

$$\frac{C_{axial}}{Q} \propto \frac{1}{\bar{z}^2\,\bar{u}(\bar{z})} \qquad (3)$$

Expressions (1), (2), and (3) are the basic equations used in the applications of similarity theory to atmospheric diffusion in the surface boundary for a continuous ground level point source. These basic equations are discussed below.

According to the similarity theory, $\overline{u}$ of Eq. (2) is completely described by another universal function $f(\zeta)$, $u_\star$, z_o, and Von Karman's constant k. As described by [6]:

$$\overline{u}(z) = \frac{u_\star}{k}\left[f(\zeta) - f(\zeta_o)\right], \quad \zeta = z/L, \ \zeta_o = z_o/L \tag{4}$$

Therefore, at the level $\overline{z}$, Eq. (2) is written

$$\frac{d\overline{x}}{dt} = \overline{u}(\overline{z}) = \frac{u_\star}{k}\left[f(\overline{\zeta}) - f(\zeta_o)\right] \tag{5}$$

Using Eqs. (1) and (2) we have:

$$\frac{d\overline{x}}{d\overline{z}} = \frac{\overline{u}(\overline{z})}{bu_\star\phi(\overline{\zeta})},$$

and substituting Eq. (5) for $\overline{u}$ and setting $\overline{\xi} = bk\overline{x}/L$, $\overline{\zeta} = \overline{z}/L$, the above differential equation in dimensionless variables $\overline{\xi}$, $\overline{\zeta}$ is

$$\frac{d\overline{\xi}}{d\overline{\zeta}} = \frac{f(\overline{\zeta}) - f(\zeta_o)}{\phi(\overline{\zeta})}\,. \tag{6}$$

When Eq. (6) is integrated, the concentration function Eq. (3) is evaluated for a downwind travel distance x where $x \cong \overline{x}$.

There are variations to the approach presented above. One such variation described by Panofsky and Prasad [5] is

$$\frac{d\bar{z}}{dt} = \frac{b}{a}\,\sigma_w$$

where a is a constant about 1.25. Combining this with Eq. (2) gives

$$\frac{d\bar{x}}{d\bar{z}} = \frac{a}{b}\,\frac{\bar{u}}{\sigma_w} = \frac{a}{b}\,\sigma_\phi^{-1} \qquad (7)$$

Empirical data on σ_ϕ as a function of z and z_o can be used with numerical integration of Eq. (7) to give $\bar{x}(\bar{z})$ [5].

Many papers on the similarity theory derive various forms for the similarity functions ϕ and f of Eqs. (1), (4). Tables A-1 and A-2 (appendix) present several of the common functions for f and ϕ (the function f is usually referred to as the integrated wind profile function).

The method developed in this report for the relation $(\bar{x}, \bar{z})$ is yet another application of the similarity equations thus described. This method consists of eliminating the need to specify both f and ϕ. Instead, a second order differential equation in $(\bar{\xi}, \bar{\zeta})$ is derived. Let

$$S(\zeta) = \frac{k}{u_*}\,\zeta\,\frac{d\bar{u}}{d\zeta} \qquad (8)$$

Hence, $f(\zeta) = \int_{\zeta_o}^{\zeta} \frac{S(\eta)}{\eta} d\eta$. Furthermore, let ϕ and S be related in the following sense:

$$\phi(\zeta) = S(\zeta)^{-1} \tag{9}$$

Equation (6) then becomes

$$\frac{d\overline{\xi}}{d\overline{\zeta}} = S(\overline{\zeta}) \int_{\zeta_o}^{\overline{\zeta}} \frac{S(\eta)}{\eta} d\eta$$

and the second derivative of this, with the appropriate substitutions, gives the second order differential equation in $(\overline{\xi}, \overline{\zeta})$, with only the function $S(\zeta)$ to be specified,

$$\frac{d^2\overline{\xi}}{d\overline{\zeta}^2} - \frac{d\overline{\xi}}{d\overline{\zeta}} \left(\frac{d}{d\overline{\zeta}} \ln S \right) - \frac{S^2}{\overline{\zeta}} = 0 \tag{10}$$

The $\overline{x}(\overline{z})$ function is now the solution to Eq. (10) given $S(\zeta)$ and the initial conditions $d\overline{\xi}/d\overline{\zeta}|_{\zeta_o} = 0$ and $\overline{\xi}(\zeta_o) = 0$. Equation (10) can be solved numerically, or for certain functions $S(\zeta)$, Eq. (10) admits of elementary closed form representations.

Table A-3 gives various solutions to Eq. (10) in closed form given the corresponding $S(\zeta)$ function. Form A of Table A-3 is the method used by Klug [2], and form B is one of the methods described in [4]. Both of these uses support the argument that ϕ is given by Eq. (9).

Particular f, ϕ, or S must be chosen on the basis of the validity of these functions in use under a given thermal stratification. For example, if the atmosphere is unstable, $L < 0$, a valid S would be the KEYPS relation or the formulation credited to Dyer [7]. If the atmosphere is stable, $L > 0$, then S could be selected as the KEYPS function, or the relation as in B of Table A-3. In the special case where $|L| \to \infty$, general agreement is for $S \equiv 1$.

The basic starting point of similarity and its application to the diffusion problem is with Eqs. (1), (2), and (3). Equations (6) and (7) are two ways to describe the $\bar{x}(\bar{z})$ relation. However, Eq. (10) using the identity Eq. (9) will be used in this report.

Replacing Proportionality with Equality

Klug [2] presents in his paper a function $f_g(\bar{\zeta})$ which describes the concentration function given by

$$\frac{C_{axial}}{Q} = \frac{f_g(\bar{\zeta})}{\bar{z}^2 \, \bar{u}(\bar{z})} \tag{11}$$

His analysis leads to the following step:

$$f_g(\bar{\zeta}) = Gg(\bar{\zeta}) \tag{12}$$

where at $\bar{\zeta} = 0$, corresponding to $|L| \to \infty$ for neutral stability, $g(0) = 1$.

G can then be evaluated according to $\left[G = \frac{C_{axial}}{Q} \cdot \bar{z}^2 \, \bar{u}(\bar{z})\right]_{\text{neutral stability}}$

given a set of data on C_{axial}/Q and the appropriate stability functions for near neutral conditions. Klug uses the test data for near neutral conditions from the Project Prairie Grass diffusion experiments [8]. His mean values of G are as follows: $G_{50m} = 0.09$, $G_{100m} = 0.12$, $G_{200m} = G_{400m} = G_{800m} = 0.13$. The subscripts refer to the distances to the various arcs used in the field test program. Klug points out that this behavior of G can be ascribed to the fact that the source height in the Prairie Grass trials was not at the surface, but at sampler height z_{ζ} = 46 cm above the ground for most runs, and at 150 cm above the ground for runs 63-68.

After G has been determined, Klug assumes that the same set of G values applies in diabatic conditions, and the function $g(\bar{\zeta})$ can therefore be evaluated. When he computed the values of g, there was no functional dependence $g(\bar{\zeta})$. Klug did find a significant correlation with $\sigma_v/u_\star$. His linear regression curve is $g(\sigma_v/u_\star) = -0.28\ \sigma_v/u_\star + 1.48$.

Klug's resulting formula for estimating the maximum downwind concentration for a continuous point source located at ground level is

$$\frac{C_{axial}(x \approx \bar{x})}{Q} = G\,\frac{(-0.28\ \sigma_v/u_\star + 1.48)}{\bar{z}^2\,\bar{u}(\bar{z})}$$

The use of this estimator is reported to be in excellent agreement with the data [2].

An f_9 function will be developed in a similar manner in this report. The function f_9 relating observed concentration to the similarity expression of Eq. (3) will be expressed as

$$f_g(\bar{\zeta}) = G(\bar{\zeta})g(\bar{\zeta}) \qquad (13)$$

The functions $G(\bar{\zeta})$ and $g(\bar{\zeta})$ will be discussed below.

Consider how the effects of h, a nonzero source release height, is taken into account. Sutton [9] used the method of images to account for the effects of an impervious earth and a nonzero source height. Consider the extension of his method to a generalized distribution of particles in the vertical using the functional form

$$\chi(z) = \exp - \frac{|z - h|^r}{B} + \exp - \frac{|z + h|^r}{B} \qquad (14)$$

The parameter r is assumed constant together with a prescribed height of emission h. B is a function of downwind distance x. The vertical spread of particles is then determined by the ratio $\chi(z)/\chi(z_{max})$ where z_{max} is the height at which the maximum concentration will occur. A concentration function for the xz plane will then be constructed as $\frac{C(x,z)}{Q} = \frac{\chi(z)}{\chi(z_{max})} \frac{C(x)}{Q}$, where $\frac{C(x)}{Q}$ is a one dimensional concentration function. Assume $\frac{C(x)}{Q} = \frac{g(\bar{\zeta})}{\bar{z}^2 \bar{u}(\bar{z})}$ for a surface based point source. Then $C(x,z) = \frac{\chi(z)}{\chi(z_{max})} g(\bar{\zeta}) \frac{1}{\bar{z}^2 \bar{u}(\bar{z})}$. Now suppose measurements are made of concentration using samplers located on a grid with a fixed sampler height, z_s. The comparison of the data to the above theoretical form should use

$$\frac{C(x,z_s)}{Q} = \frac{\chi(z_s)}{\chi(z_{max})}\, g(\bar{\zeta})\, \frac{1}{\bar{z}^2\, \bar{u}(\bar{z})} \qquad (15)$$

Comparing Eqs. (11), (13), and (15) yields

$$G(\bar{\zeta}) = \frac{\chi(z_s)}{\chi(z_{max})} \qquad (16)$$

To find z_{max} set the derivative of Eq. (14) with respect to z to zero and solve for $z = z_{max}$. For $0 \leq z < \infty$, the root to $\frac{\partial\chi(z)}{\partial z} = 0$ is an absolute maximum. With $\eta = \frac{z_{max}}{h}$ the solution for z_{max} is derived from

$$\mathrm{TANH}\{\mu(1 + \eta)^r - \mu(1 - \eta)^r\} = \eta, \text{ where } \mu = \frac{h^r}{2(r - 1)B} \qquad (17)$$

and TANH is the Hyperbolic tangent function.

Now B in Eq. (17) can be found by invoking the definition of $\bar{z}$[1,2,3]; that is, $\bar{z}$ is the first moment of particle distribution in the vertical

$$\bar{z} = \frac{\int_0^\infty z\, C(x,z)dz}{\int_0^\infty C(x,z)dz} = \frac{\int_0^\infty z\chi(z)dz}{\int_0^\infty \chi(z)dz} \qquad (18)$$

Using Eq. (14),

$$\bar{z} - h\delta(1/r, \frac{h^r}{B}) = B^{1/r}\, \frac{\Gamma(2/r)}{\Gamma(1/r)}\, [1 - \delta(2/r, \frac{h^r}{B})] \qquad (19)$$

where $\Gamma(\alpha) = \int_0^\infty \eta^{\alpha-1} e^{-\eta} d\eta$ is the gamma function, and $\delta(\alpha,\varepsilon) =$

$$\frac{\int_0^\varepsilon \eta^{\alpha-1} e^{-\eta} d\eta}{\Gamma(\alpha)}.$$

Note that if $\frac{h^r}{B} \to 0$ then

$$B^{1/r}(\overline{z}) = \frac{\Gamma(1/r)}{\Gamma(2/r)}\,\overline{z} \qquad (20)$$

Remember $\overline{z}(\overline{x})$ is known and for $\overline{x} \simeq x$ B is a function of downwind travel distance, $B = B(x)$ (actually B is the vertical size parameter for the diffusing cloud, for if $h = 0$, $r = 2$, then $B = 2\sigma_z^2$ where σ_z is a commonly used descriptor of vertical cloud size to be defined later). Inserting $B(x)$ into Eq. (17) defines z_{max} which indicates $G(\overline{\zeta}) = G(x)$ which was shown empirically by Klug (see page 10 of this report).

Similarity Theory and the Vertical Distribution $\overline{z^2}$

The statistic $\overline{z^2}$ of the distribution of diffusing particles from the position they would otherwise occupy as a result of average displacement $\overline{z}$ is defined as follows:

$$\overline{z^2} = \int_0^\infty z^2 C(x,z)dz \Big/ \int_0^\infty C(x,z)dz \qquad (21)$$

substituting Eq. (14) in the C(x,z) function as shown on page 11, then

$$\overline{z^2} = \int_0^\infty z^2 \chi(z)dz \Big/ \int_0^\infty \chi(z)dz = B^{2/r}\frac{\Gamma(3/r)}{\Gamma(1/r)} + h^2 \qquad (22)$$

For simplicity $r = 2$ gives the familiar form

$$B = 2\sigma_z^2 = 2(\overline{z^2} - h^2) \qquad (23)$$

where the quantity σ_z is the familiar standard deviation, $(\overline{z^2} - \overline{z}^2)^{\frac{1}{2}}$, where $\overline{z} = h$, of a normally distributed (Gaussian) probability function, but σ_z is known as the vertical size parameter of a diffusing cloud in the context of this report.

Substituting $B = 2\sigma_z^2$ in Eq. (14) and with $r = 2$,

$$x(z) = \exp[-\tfrac{1}{2}(z - h)^2/\sigma_z^2] + \exp[-\tfrac{1}{2}(z + h)^2/\sigma_z^2] \qquad (24)$$

The above form, Eq. (24), is widely used in concentration predictors as the vertical distribution function [9].

Evaluation

Now that the diffusion model has been defined, constants and/or functions like b, r, and $g(\overline{\zeta})$ can be evaluated. First, the values of b and r will be found by using data on σ_z^2 as defined in Eq. (23) from Haugen et al. [10]. The predictor is

$$\sigma_z^2 = \overline{z^2} - h^2 = B^{2/r}\,\frac{\Gamma(3/r)}{\Gamma(1/r)} \qquad (25)$$

There are 48 runs for which σ_z at $\chi = 100$ meters could be calculated. The similarity functions for $S(\zeta)$ are as follows (Table A-3):

$$S(\zeta) = \begin{cases} (1 - 15\ z/L)^{-1/4}, & z/L < 0 \\ (1 + \beta\ z/L), & z/L > 0 \end{cases} \tag{26}$$

where $\beta = \frac{z_r/L - R_i}{z_r/L\ R_i}$ with $z_r = 2$ meters and R_i is the Richardson number for the 2-meter level. Von Karman's constant k is set at 0.40. The value for r was chosen to be 1.5 for the following reasons. Elliot's [11] analysis of Prairie Grass data for the vertical concentration distribution did not reveal any substantial variation of shape with stability, and his average r was 1.49. The value of b in Eq. (1) was adjusted to obtain the best fit of Eq. (25) to Haugen's σ_z data. A value of b = 0.48 was obtained.

The resulting value of bk = 0.19 is not far from the experimental value of 0.18 obtained by Pasquill from these same data [3]. Figure 1 shows the comparison of theory, i.e., Eq. (25), to the σ_z data. Very good agreement is obtained for all L such that $1/L < 0.03$. There is fair agreement for the very stable condition $1/L \geq 0.03$.

The function $g(\overline{\zeta})$ can now be determined from the data by the relation $g = \frac{C_{meas}}{Q} \frac{\overline{z}^2\,\overline{u}(\overline{z})}{G(x)}$ where $\frac{C_{meas}}{Q}$ is the measured field of concentration for a run normalized by the source strength for that run. Fifty runs were obtained from approximately 70 tests of the Prairie Grass Program to utilize in evaluating g. As with Klug [2], no relation such as $g = g(\overline{\zeta})$ was found. Instead, after finding an average g, $\overline{g}$, for each run, 50 $\overline{g}$ values were correlated with $\sigma_v/u_\star$. The linear regression is

$$g(\sigma_v/u_\star) = -0.035\sigma_v/u_\star + 0.186 \tag{27}$$

This regression line and the data are plotted in Figure 2. To compare this linear regression line to that of Klug's, Eq. (27) has to be scaled by 1/0.13. With this scale $\frac{g(\sigma_v/u_\star)}{0.13} = -0.27\ \sigma_v/u_\star + 1.43$. The comparison is in good agreement considering the different approach taken by the two methods. (See page 10 this report.)

Our prediction formula for concentration in the xz plane from a continuous point source for a near ground level release is

$$C(x,z) = \frac{\chi(z)}{\chi(z_{max})} \quad \frac{(-0.035\ \sigma_v/u_\star + 0.186)}{\overline{z}^2\ \overline{u}(\overline{z})} \tag{28}$$

The data of Tables A-5, A-6, and A-7 depict the applicability of the similarity theory to the diffusion problem. The data on σ_z comparisons in Table A-5 show very good agreement with the overall ratio of predicted $(\overline{z^2} - h^2)^{1/2}$ to observed σ_z values equal to 1.04. The concentration comparisons of Table A-6 give good agreement. There is an anomalous value of the 800-meter value of concentration for run 39. But the overall ratios of predicted to observed concentrations are

$r_{50} = 1.02$ $r_{200} = 1.06$ $r_{800} = 1.29$

$r_{100} = 1.00$ $r_{400} = 1.21$

The comparison of the vertical distribution Eq. (14) using $r = 1.5$ is given in Table A-7. Here Elliot's [12] data on the ratio of vertical concentration at height z to that at height $z = 0.5$ is used. The distribution Eq. (14) does an excellent job.

CONCLUSIONS

The Similarity Theory aided with empirical derivations has been shown to be applicable to the continuous point source problem of atmospheric diffusion. The stability functions f, ϕ, and S allow the theory to cover all atmospheric stabilities of neutral, stable, or unstable.

This report has shown that the solution to a second-order ordinary differential equation in (ζ, ξ), Eq. (10), which needs only a function for $S(\zeta)$, the nondimensional wind shear, specifies the change of $\bar{z}$ versus $\bar{x}$. (Note that the integration can be carried out even if S is in the form of data points directly computed from a wind profile, although this was not done in this report.)

The solution to Eq. (10) in $\overline{z}$ and $\overline{x}$ is then used to compute the concentration C. This report has also developed a proportionality for Eq. (3) based on an analytical treatment of the vertical diffusion term (Eq. 14).

The vertical size parameter $\overline{z^2}$ has been given a functional form (Eq. 22) and has been shown to be in excellent agreement with data over all atmospheric stabilities.

A restraint on h, the source emission height, is that it should not be greater than a few meters above ground level. For an excellent summary of restrictions on h and $\overline{x}$ in similarity theory see Pasquill [16], section 3.3.

REFERENCES

1. Gifford, F. A., 1962, "Diffusion in the Diabatic Surface Layer," J. Geophys. Res., 67, 3207.

2. Klug, W., 1968, "Diffusion in the Atmospheric Surface Layer: Comparison of Similarity Theory With Observations," Quart. J. Roy. Meteorol. Soc., 94, 555.

3. Pasquill, F., 1966, "Lagrangian Similarity and Vertical Diffusion From A Source at Ground Level," Quart. J. Roy. Meteorol. Soc., 92, 185.

4. Chaudhry, F. H. and R. N. Meroney, 1969, "Turbulent Diffusion in a Stably Stratified Shear Layer," ECOM C-0423-5, Fluid Dynamics and Diffusion Laboratory, College of Engineering, Colorado State University, Fort Collins, CO.

5. Panofsky, H. A. and B. Prasad, 1965, "Similarity Theories and Diffusion," Intern. J. Air and Water Poll., 9, 419.

6. Monin, A. S. and A. M. Obukhov, 1954, "Basic Regularity in Turbulent Mixing in the Surface Layer of the Atmosphere," USSR Academy of Science, Works of the Geophysical Institute.

7. Dyer, A. J. 1967, "The Turbulent Transport of Heat and Water Vapour in an Unstable Atmosphere," Quart. J. Roy. Meteorol. Soc., 96, 715-721.

8. Barad, M. L., 1958, "Project Prairie Grass, A Field Program in Diffusion," Geophys. Res. Papers, 1, 59.

9. Sutton, O. G., 1953, Micrometeorology, New York, McGraw-Hill.

10. Haugen, D. A., M. L. Barad, and P. Antanaitis, 1961, "Values of Parameters Appearing in Sutton's Diffusion Models," J. Meteorol., 18. 368.

11. Elliot, W. P., 1961, "The Vertical Diffusion of Gas From A Continuous Source," Intern. J. Air and Water Poll., 4, 33.

12. Elliot, W. P., 1960, "A Discussion of the Calder Equation for Diffusion From A Continuous Point Source," Geophysics Research Directorate, Air Force Cambridge Center, Air Research and Development Command, Bedford, MA.

13. Yamamoto, G., 1959, "Theory of Turbulent Transfer in Non-Neutral Conditions, J. Meteorol. Soc. Japan, 37, 60.

14. Businger, J. A., 1966, "Proceedings of the Symposium on the Arctic Heat Budget and Atmospheric Circulation," Lake Arrowhead, CA., Jan-Feb, 1966, p 305.

15. Monin, A. S., 1959, "Smoke Propagation in the Surface Layer of the Atmosphere," Advances in Geophysics, 6, pp 331-344, F. N. Frenkiel and P. A. Sheppard (Eds) Academic Press, Inc., New York.

16. Pasquill, F., 1974, "Atmospheric Diffusion," *John Wiley and Sons*, Sussex, England.

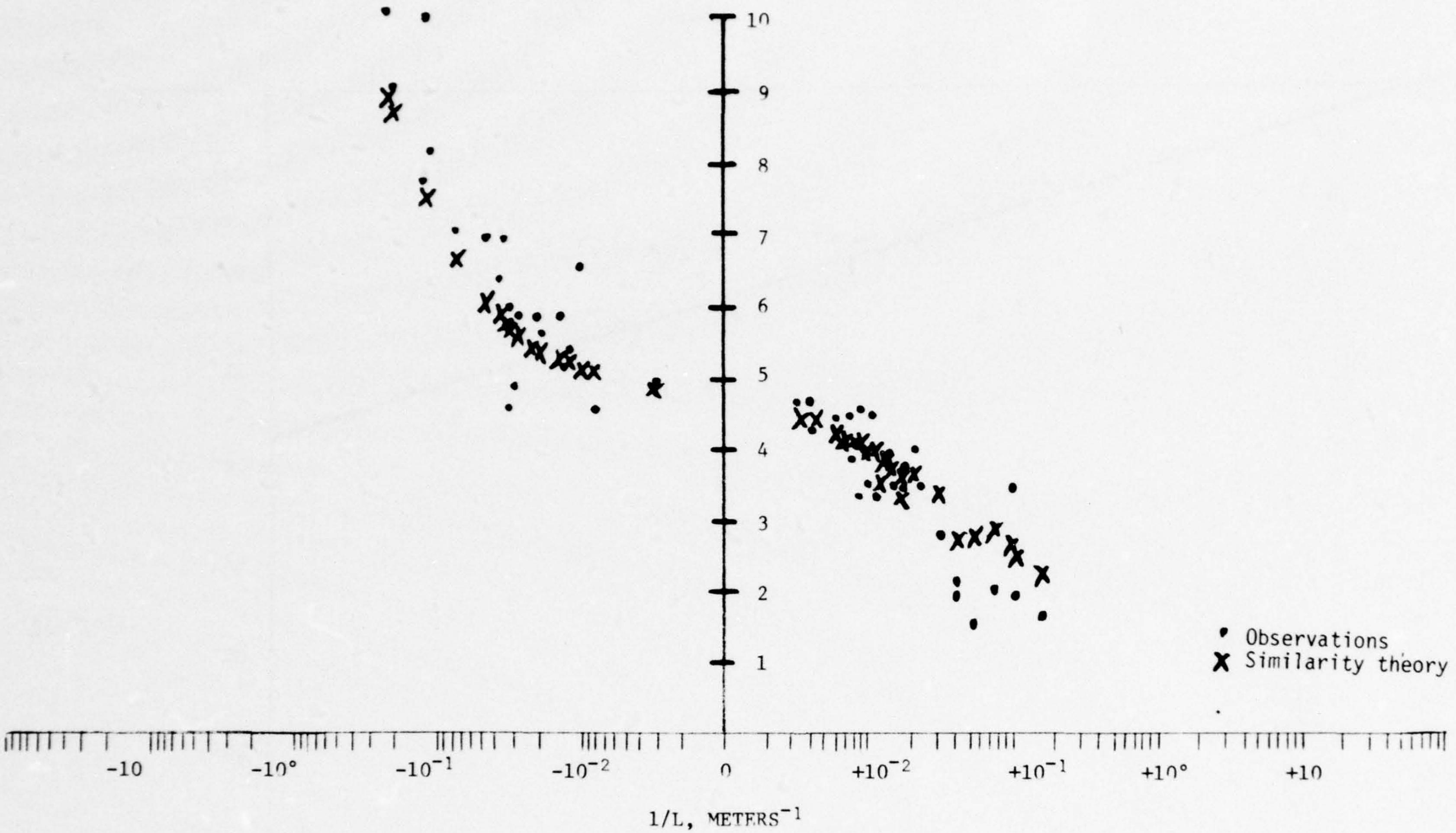

Figure 1. Vertical spread $[\overline{z}^2 - h^2]^{\frac{1}{2}}$ at 100 m.

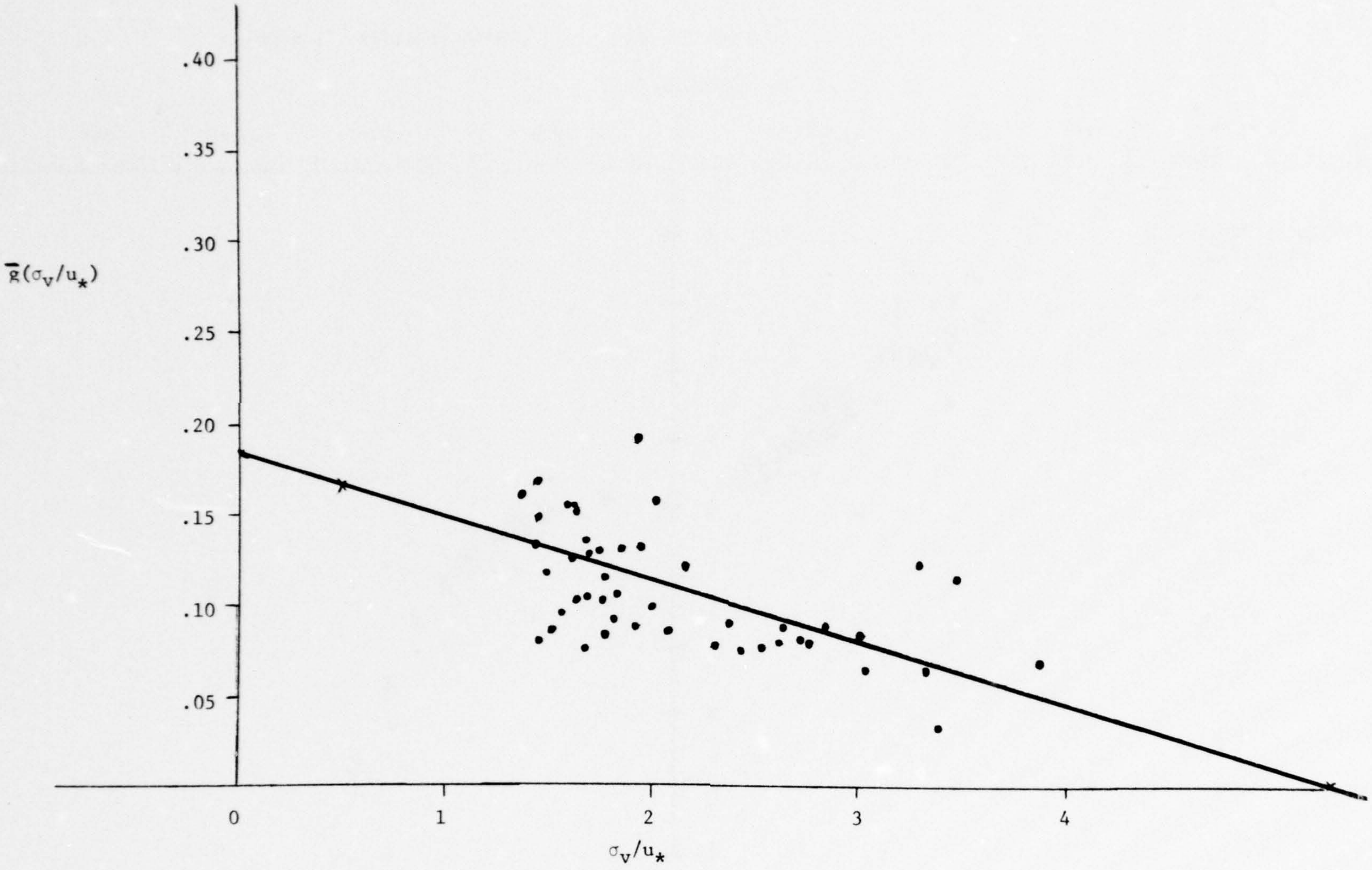

Figure 2. Mean values of g versus σ_v/u_*. The data points and the regression curve.

APPENDIX

CALCULATION PROCEDURES

The calculation procedures for finding L, $u_\star$, $\beta(R_i)$, R_i, and ϕ_M (a numerical calculation of $S(\zeta)$ from profile data) are as follows:

$$R_i = g/\overline{T}\ \frac{(\Delta T + \Gamma)}{\Delta V^2}\ Z_g\ \Delta \ln Z \text{ where}$$

$\overline{T}$ = °C + 273.16

Γ = 0.0098 deg k/m

g = 9.8 m/sec

Z_g = geometric mean of the profile layer

V is the wind profile data, m/sec

In stable flow,

$$Z/L = \frac{kg\ \partial\theta/\partial Z}{u_\star\Theta\ \partial V/\partial Z} = \frac{kg\ \Delta\Theta}{u_\star\Theta\Delta V},\quad 1/L = \frac{\Sigma Z/L}{\Sigma Z}$$

$$\phi_M = [1 + \frac{\Delta V_1 - \Delta V_2}{\Delta V_1 - 2\Delta V_2}] = \phi_H$$

$$u_\star = k\phi_m^{-1}\ \Delta V/\Delta \ln Z$$

$$\beta = R_i^{-1}\ \frac{\Delta V_2 - \Delta V_1}{\Delta V_1}$$

In unstable flow,

$$Z/L = R_i = \frac{u_\star^{3\,c} p\rho\Theta}{kZgH},\quad 1/L = \frac{\Sigma\ R_i Z_i}{\Sigma\ Z_i}$$

$$H = c_p \rho K_H \frac{\partial \Theta}{\partial Z}$$

$$K_H = \frac{k u_\star Z}{\rho_H}$$

$$\phi_H = \phi_M^2$$

$$\phi_M = [1 - \frac{\Delta V_1^4 - \Delta V_2^4}{\Delta V_1^4 - 2\Delta V_2^4}]^{-1/4}$$

$$u_\star = k\phi_m^{-1} \, \Delta V/\Delta \ln Z$$

$$\gamma = 15$$

where

c_p = 2.24 cal/g deg

ρ = 0.0012 g/cm^3

k = 0.4

Θ = °C + 273.16

TABLE A-1

INTEGRATED WIND PROFILE FUNCTIONS COMMONLY IN USE

A. KEYPS (Yamamoto [13])

$f(\zeta) = \delta - 2\,\mathrm{TAN}^{-1}\delta - 2\,\mathrm{TANH}^{-1}\delta$, where $\delta^4 - \alpha\zeta\delta^3 - 1 = 0$ with α about 7, $\zeta = z/L$

B. Monin-Obukhov [6]

$$f(\zeta) = \begin{cases} \ln\zeta + \beta\zeta, & \beta > 0 \\ \ln\zeta & \beta = 0 \end{cases}$$

B1. As above but with β variable with $\beta = \dfrac{\zeta - R_i}{\zeta R_i}$.

$\zeta = z_r/L$, z_r a reference height,

R_i = Richardson number at level z_r

C. Businger, Dyer [14]

$$f(\zeta) = \ln\frac{(1 - \varepsilon)}{(1 + \varepsilon)} + 2\,\mathrm{TAN}^{-1}\varepsilon$$

where $\varepsilon = (1 - \gamma\zeta)^{1/4}$, γ about 15

TABLE A-2

THE UNIVERSAL FUNCTION $\phi(\zeta)$ OF EQ. (1)

A. Monin (1959) [15]

$\phi(\zeta) = [1 - \left(\frac{df}{d\zeta}\right)^{-1}]^{1/4}$ where f is the integrated wind profile function.

B. Gifford [1]

$\phi(\zeta) = 1/2\ \{[\frac{1 + (\alpha - 1)\zeta}{1 + \alpha\zeta}]^{1/4} + 1\}, \alpha > 5$

C. KOEHLER (1967) [16]

$\phi(\zeta) = (1 + \beta\zeta)^{-1}, \beta > 0$

TABLE A-3

THE RELATION OF $\overline{x}$ AND $\overline{z}$ USING EQ. (10) AND THE FOLLOWING $S(\overline{\zeta})$ FUNCTIONS (using the initial conditions $d\overline{\xi}/d\overline{\zeta}|_{\zeta_o} = 0$, $\overline{\xi}(\zeta_o) = 0$).

A. KEYPS [13]

$S(\overline{\zeta})$ given by $S^4 - \alpha\overline{\zeta}\, S^3 - 1 = 0$

then

$$\overline{\xi} = \frac{1}{\alpha S^2}\left[\frac{S(S^4 + 9)}{3} - (S^4 - 2S^2 - 3)\tan^{-1}S - 1/2(S^4 - 3)(S_o - 2\tan^{-1}S_o)\right.$$

$$\left. + 1/2(S^4 + 2S^2 - 3)\ln\frac{(1 + S_o)(1 - S)}{(1 - S_o)(1 + S)}\right]$$

where $S_o^4 - \alpha\zeta_o\, S_o^3 - 1 = 0$

B. Monin-Obukhov [4]

$S = 1 + \beta\overline{\zeta}$

$$\overline{\xi} = \frac{1}{12\beta}\{12\varepsilon\ln\zeta/\zeta_o + 6\varepsilon^2\ln\zeta/\zeta_o + 12(\varepsilon - \varepsilon_o) + 3(\varepsilon - 3\varepsilon_o)(\varepsilon - \varepsilon_o)$$

$$+ 2(\varepsilon - \varepsilon_o)^2(2\varepsilon - \varepsilon_o)\}$$, where $\varepsilon = \beta\overline{\zeta}$, $\varepsilon_o = \beta\zeta_o$

C. Businger, Dyer [11]

$S = (1 - \alpha\overline{\zeta})^{-1/4}$

$$\overline{\xi} = \frac{8}{3\alpha}\{\varepsilon^2 - \varepsilon_o{}^2 + 1/2\ln\frac{(1 - \varepsilon^2)(1 + \varepsilon_o{}^2)}{(1 + \varepsilon^2)(1 - \varepsilon_o{}^2)} + (\varepsilon^3/2)\ln\frac{(1 + \varepsilon)(1 - \varepsilon_o)}{(1 - \varepsilon)(1 + \varepsilon_o)}$$

$$+ \varepsilon^3(\tan^{-1}\varepsilon_o - \tan^{-1}\varepsilon)\}$$

where $\varepsilon = S^{-1}$, $\varepsilon = S_o^{-1}$

TABLE A-4

VALUES OF $G^{-1}(\bar{x})$ FOR TYPICAL STABILITY CONDITIONS

(Z_o = 0.007 m, b = 0.48, k = 0.4, r = 1.5, h = 0.46 m

Stability	L Value Used	Distance From Source, x				
		50 m	100 m	200 m	400 m	800 m
Extremely Unstable $L > -5$	-1	1.07	1.02	1.00	1.00	1.00
Moderately Unstable $-100 \leq L \leq -5$	-50	1.27	1.04	1.01	1.00	1.00
Near Neutral $\lvert L \rvert > 100$	-200	1.30	1.12	1.05	1.02	1.00
	+200	1.35	1.15	1.07	1.03	1.01
Stable $10 < L < 100$	+50	1.42	1.19	1.09	1.05	1.02
Very Stable $L < 10$	+1	2.17	1.63	1.36	1.26	1.13

TABLE A-5

COMPARISON OF VERTICAL SPREAD $[\overline{z}^2-h^2]^{1/2}$ AT 100 m. σ OBSERVED (HAUGEN, ET AL.), $[\overline{z}^2-h^2]^{1/2}$ PREDICTED, AND R, RATIO OF PREDICTED TO OBSERVED

Run No.	σ(m)	$[\overline{z}^2-h^2]^{1/2}$	R	Run No.	σ(m)	$[\overline{z}^2-h^2]^{1/2}$	R
14	1.4	1.18	.74	41	3.4	3.96	1.16
15	7.7	7.46	.97	42	4.4	4.08	.93
16	10.1	8.86	.88	43	7.0	6.60	.94
17	3.7	3.57	.96	44	6.3	5.79	.92
18	2.7	3.30	1.22	45	4.5	5.04	1.12
19	6.9	6.01	.87	46	3.3	4.00	1.21
20	5.8	5.37	.93	48	5.8	5.2	.90
21	4.2	4.32	1.03	49	4.5	5.69	1.26
22	4.6	4.32	.94	50	5.9	5.67	.96
24	4.6	4.38	.95	51	4.8	5.54	1.15
25	9.0	8.65	.96	52	10.0	7.44	.74
26	5.7	5.6	.98	54	3.9	3.58	.92
27	5.8	5.54	.96	55	4.4	4.17	.95
29	3.4	3.46	1.02	56	4.4	3.91	.89
30	5.6	5.33	.95	57	4.9	4.85	.99
31	6.5	5.07	.78	58	1.5	2.75	1.83
32	1.6	2.18	1.36	59	2.0	2.90	1.45
33	5.1	5.17	1.01	60	3.9	3.80	.97
34	5.3	5.14	.97	61	4.8	5.60	1.17
35s	3.4	3.74	1.10	62	6.9	5.73	.83
36	1.9	2.54	1.34	65	3.4	3.28	.96
37	4.5	4.02	.89	66	2.1	2.70	1.29
38	3.8	4.06	1.07	67	3.3	3.49	1.06
40	3.4	2.65	.78	68	1.9	2.72	1.43

average ratio $R_{avg} = 1.04$

TABLE A-6

VALUES OF CALCULATED PARAMETERS FOR ALL PRAIRIE GRASS RUNS, AND RATIOS OF PREDICTED CONCENTRATIONS BY THEORY TO MEASURED CONCENTRATIONS FOR THOSE RUNS SELECTED BY THIS STUDY

Run No.	L	$U_\star$	$(R_i)2m$	R_{50}	R_{100}	R_{200}	R_{400}	R_{800}
1	-14.7	.197	*					
2	-27.0	.128	*					
3	0.35	.020	.5					
4	0.35	.020	.5					
5	-32.3	.434	*	.93	.93	1.03	1.31	1.46
6	-111.	.429	*	1.08	1.15	1.27	1.52	1.65
7	-14.1	.336	*					
8	-25.6	.333	*	.46	.47	.48	.68	.91
9	-19.6	.434	*	1.04	1.05	1.07	1.17	1.32
10	-11.0	.358	*	.69	.75	.65	.75	
11	-90.9	.546	*	.95	.93	.76	.76	.81
12	-58.8	.586	*	1.16	1.13	.91	.85	.64
13	0.35	.020	.5					
14	0.35	.020	.5					
15	-8.13	.253	*	.52	.53	.50	.53	.88
16	-4.59	.267	*					
17	-56.0	.209	*	.84	.84	.98	1.21	1.46
18	31.4	.213	*	.94	1.06	1.24	1.45	1.69
19	-22.2	.460	*					
20	-50.0	.680	*	1.15	1.30	1.24	1.43	1.65
21	242.	.425	.007	.74	.76	.85	.93	1.02
22	238.	.507	.008	.80	.79	.80	.89	1.05
23	259.	.414	.007	.97	1.00	1.05	1.18	1.28
24	302.	.397	.006	1.09	1.13	1.15	1.14	1.25
25	-5.00	.222	*					
26	-34.5	.474	*	1.22	1.18	1.09	1.28	1.64
27	-37.0	.459	*	1.20	1.29	1.14	1.07	1.01
28	26.8	.167	.043	1.24	1.38	1.84	2.15	2.17
29	40.4	.273	.033					
30	-52.6	.504	*					
31	-100.	.572	*	1.18	1.34	1.43	1.67	1.24
32	6.31	.094	.102	1.81	1.17	1.29	1.40	1.40
33	-76.9	.547	*	.92	.87	.83	1.01	1.36
34	-83.3	.679	*	1.12	1.03	.92	.89	.82
35	2.20	.051	.224					
35s	65.5	.253	.023	.88	.96	1.15	1.38	1.53
36	9.21	.084	.091	1.61	1.29	1.68	2.59	1.72
37	114.	.315	.014	1.03	1.16	1.45	1.86	2.94
38	129.	.295	.013	.82	.74	.77	.80	.87

Table A-6 (Cont)

Run No.	L	U_*	$(R_i)_{2m}$	R_{50}	R_{100}	R_{200}	R_{400}	R_{800}
39	7.32	.102	.104	1.33	1.92	2.59	3.27	
40	10.0	.101	.086					
41	105.	.320	.015	.60	.55	.60	.57	.56
42	136.	.421	.012	.93	.99	1.18	1.75	2.02
43	-13.5	.395	*	.89	.99	.89	1.09	.98
44	-27.8	.443	*	1.02	1.08	1.08	.96	1.16
45	-125.	.430	*	1.06	.99	.90	.91	.77
46	112.	.372	.015	.85	1.06	1.40	1.85	2.89
47	-4.67	.269	*					
48	-7.14	.564	*	1.30	1.21	1.21	1.13	1.04
48s	-5.55	.257	*					
49	-31.3	.494	*	1.19	.98	.98	1.20	1.19
50	-32.3	.493	*	.96	1.02	1.29	1.41	2.29
51	-37.0	.498	*	1.04	1.09	1.20	1.54	2.93
52	-8.33	.344	*					
53	5.37	.103	.129	1.45	1.26	1.43	1.83	2.10
54	47.1	.271	.030	.84	.85	.96	.95	.99
55	166.	.418	.010	.90	.87	.94	1.19	1.28
56	91.0	.330	.018	.85	.90	1.04	1.11	1.14
57	-333.	.525	*	1.11	1.33	1.11	1.22	1.31
58	18.0	.109	.053	1.02	.65	.61	.63	.64
59	13.3	.150	.075	.80	.56	.59	.55	.62
60	70.6	.320	.022	.78	.77	.77	.93	.93
61	-34.5	.572	*	1.33	1.25	1.07	1.07	1.23
62	-29.4	.381	*	.96	.84	.69	.62	.63
63	0.35	.020	.5					
64	0.35	.020	.5					
65	59.1	.299	.025	1.20	.89	.87	.87	1.02
66	23.9	.188	.049					
67	84.7	.299	.019	1.14	.85	.80	.84	.92
68	24.3	.160	.048	1.05	.92	1.04	1.22	.97
	overall average ratios			1.02	1.00	1.06	1.21	1.29

*For unstable conditions $z/L = R_i$

TABLE A-7

COMPARISON OF RATIOS OF GAS CONCENTRATIONS AT HEIGHT Z TO CONCENTRATION AT 0.5 M. OBSERVED R_o, AND PREDICTED R_p AT 100 M FROM RELEASE POINT (R_o VALUES FROM ELLIOT [5])

Run No.	Z cm	R_o	R_p	Run No.	Z cm	R_o	R_p	Run No.	Z cm	R_o	R_p
17	100	.95	.93	18	100	.93	.92	19	100	.96	.97
	150	.87	.85		150	.82	.83		150	M	.93
	250	.70	.67		250	.61	.63		250	.73	.83
	450	.42	.35		450	.25	.30		450	.52	.61
	750	.14	.096		750	.022	.068		750	.30	.34
20	100	.98	.96	21	100	.94	.95	22	100	.94	.95
	150	.96	.91		150	.87	.88		150	.88	.88
	250	.84	.80		250	.74	.73		250	.70	.73
	450	.55	.56		450	.44	.44		450	.39	.44
	750	.28	.28		750	.16	.17		750	.14	.16
26	100	.92	.97	27	100	.94	.96	30	100	.98	.96
	150	.88	.92		150	.85	.92		150	.94	.91
	250	.71	.81		250	.69	.81		250	.79	.80
	450	.44	.58		450	.48	.58		450	.58	.56
	750	.20	.30		750	.26	.30		750	.29	.27
33	100	.94	.96	37	100	.95	.94	48	100	.91	.90
	150	.88	.91		150	.86	.87		150	.83	.78
	250	.77	.79		250	.76	.71		250	.65	.53
	450	.48	.54		450	.47	.41		450	.37	.19
	750	.22	.26		750	.17	.14		750	.12	.026
43	100	.95	.97	45	100	.95	.96	49	100	.94	.97
	150	.90	.94		150	.86	.90		150	.91	.92
	250	.86	.85		250	.67	.78		250	.69	.81
	450	.63	.65		450	.36	.52		450	.53	.59
	750	.32	.39		750	.12	.24		750	.21	.31
55	100	.97	.95	57	100	.96	.96	60	100	.96	.94
	150	.89	.88		150	.92	.90		150	.88	.86
	250	.73	.72		250	.76	.77		250	.73	.69
	450	.43	.43		450	.49	.51		450	.39	.37
	750	.17	.15		750	.21	.22		750	.12	.11

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