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A COMPARISON OF ESTIMATION PROCEDURES
FOR OVER-WATER PLUME DISPERSION

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1. INTRODUCTION

Effluent transport and diffusion over water is receiving increased study, largely because of the current interest in off-shore nuclear power plants. Dispersion estimations identical to those used over land are open to question because, for given weather conditions (e.g., clear skies, moderate wind), the over-water turbulence will differ greatly from that over land. This paper attempts to assess the predictive capability of techniques similar to those in general use, but which utilize descriptions of turbulence perhaps more appropriate to over-water flows.

2. THEORETICAL DEVELOPMENT

2.1 Gaussian Plume Formulation

The normal or Gaussian distribution function is a fundamental solution of the Fickian diffusion [Sutton (1953)]. As such, it is strictly applicable only for large diffusion time and homogeneous, stationary conditions. However, many studies have verified its practical utility over land [Gifford (1968)]. In view of the horizontally nearly homogeneous and more or less stationary conditions that may be expected over the ocean, the formulation seems to be a reasonable choice for over-water flow as well. The concentration $\bar{\chi}$ due to a continuous source of strength Q_o located at the x-y origin at elevation h is [Gifford (1968)]:

$$\frac{\bar{\chi}}{Q_o} = \frac{1}{2\pi\sigma_y\sigma_z\bar{u}} \exp\left[-\frac{y^2}{2\sigma_y^2}\right] \cdot \left\{\exp\left[-\frac{(z-h)^2}{2\sigma_z^2}\right] + \exp\left[-\frac{(z+h)^2}{2\sigma_z^2}\right]\right\} \quad (1)$$

For practical applications, a number of authors [e.g., Gifford (1961), the ASME (1968, 1973), Briggs (1973)] have presented the dispersion coefficients σ_y and σ_z either graphically, or as analytic functions of distance x, for a variety of stability conditions. The choice of stability category is typically made using easily observed variables such as "surface" wind speed, insolation, temperature gradient, and/or fluctuations in wind speed and direction. Nearly all such dispersion coefficients are based on data gathered over open land of modest roughness and, strictly speaking, should be used only for calculations over similar terrain. Within this restriction, the time-averaged concentration estimates made with this technique can be expected to be accurate within a factor of 2 [Islitzer and Slade (1968)] or 3 [Turner (1969)].

A similar methodology for over-water use is desirable. However, the dispersion parameters obtained over land and classified according to over-land stabilities cannot be expected to be directly applicable over the sea. As Van der Hoven (1967) has pointed out, the smooth water surface results in substantially less mechanically generated turbulence than over land, while the air-water temperature difference will either enhance or hinder convection. Evaporation may also significantly affect atmospheric stability [Lumley and Panofsky (1964)] and the resultant diffusion.

An extensive set of over-water diffusion experiments from which characteristic dispersion coefficients might be deduced is not yet available. The work being done at Brookhaven National Laboratory [Michael, et al. (1973a,b)] should help to remedy this situation. In the meantime, diffusion estimates can only be made by means of expressions, often empirical, for σ_y and σ_z which utilize some sort of observed over-water wind data that can serve to characterize the turbulence. This approach has been adopted here. Its adequacy can be judged by comparing its predictions to the relatively few observations reported thus far in the literature.

2.2 Characterization of Over-water Stability and Roughness Effects.

Detailed simultaneous observations of wind, temperature, and humidity profiles and of sea surface conditions are unlikely to be available at ocean sites for which diffusion estimates are needed. For this study, techniques were therefore chosen which require only data obtainable from quite simple instrumentation.

The standard deviation of the horizontal wind angle, σ_θ, is known to be strongly related to σ_y [Van der Hoven (1967), Islitzer and Slade (1968)]. In fact, for over-land use, Slade (1966) has associated a particular σ_θ value with each Pasquill stability class to provide a quantitative means of choosing the appropriate category. However, σ_θ contains an implicit description of the site roughness as well as the convective activity [Cramer, et al. (1958), Gifford (1972)]. Here, σ_θ is assumed to provide an adequate description of the local turbulence; the problem is then to find σ_y curves based on σ_θ which correctly predict the lateral diffusion. Slade (1962) and Van der Hoven (1967) have used σ_θ in a somewhat similar fashion to estimate coastal region diffusion. They did not attempt to compare their results to observations, probably because of lack of data.

The connection between σ_θ and the vertical diffusion parameter σ_z is not so well defined. Cramer, et al. (1964) have suggested that σ_z, like σ_y, can be quantitatively related to σ_θ, and the ASME Guide (1968, 1973) also supplies an explicit scheme for this. One other technique seems possible; it is based on a formulation for σ_z in which the roughness and stability effects are considered separately [Smith (1972)].

2.3 Expressions for σ_y and σ_z.

Obvious first choices are the Pasquill-Gifford (P.-G.) curves for σ_y and σ_z as functions of x. These are given in Figures 1 and 2, where the value of σ_θ appropriate to each curve [Slade (1966)] has been indicated. The usual letter-stability classification (e.g., "D" = neutral) has been dropped, since it is incorrect over water. Figures 1 and 2 also show the dispersion parameters suggested by Briggs (1973); these curves were deduced in part from long-range experiments, and so may be somewhat more reliable than their P.-G. counterparts at large distances.

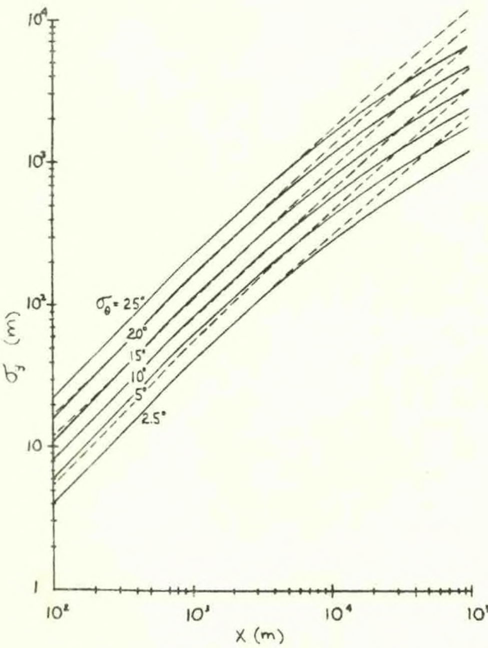

Figure 1. Pasquill-Gifford (broken) and Briggs (solid) curves for lateral dispersion coefficient.

Some expressions for σ_y make explicit use of the local value of σ_θ. For example Cramer, et al. (1964) use a power-law in x:

$$\sigma_y = \sigma_\theta \, x_r \, (x/x_r)^p \quad , \qquad (2)$$

where p depends on stability and x_r is a reference length. For over-land use, Cramer, et al. (1964) supply the exponents listed in Table 1, classified by σ_θ. Similar relations are suggested in the ASME Guide (1968, 1973).

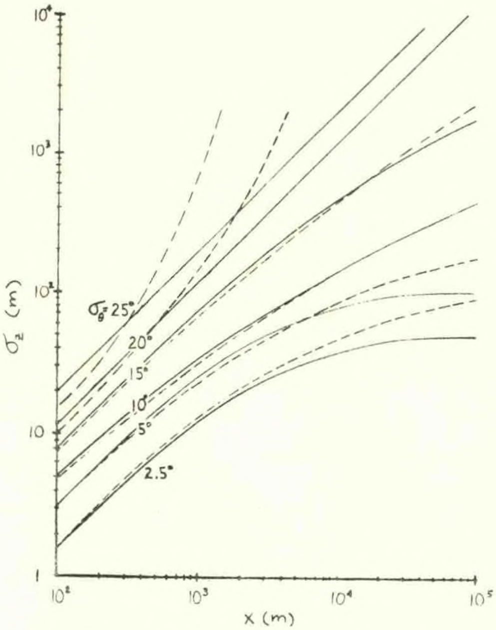

Figure 2. Pasquill-Gifford (broken) and Briggs (solid) curves for vertical dispersion coefficient.

Table 1

Power-law exponents for $\sigma_y = \sigma_\theta x_r (x/x_r)^p$, $\sigma_z = \sigma_\theta x_r (x/x_r)^q$, from Cramer, et al. (1964), for use over land

Stability	σ_θ (deg)	p $200 \leq x \leq 800$ m	q $50 \leq x \leq 800$ m
↑	3	0.45	0.86
	4	0.56	0.86
	5	0.64	0.88
	6	0.71	0.91
	7	0.80	0.96
Stable	8	0.85	1.13
Neutral	10	0.85	1.29
Unstable	12	0.85	1.55
	20	0.85	1.74
↓	25	0.85	1.89

Over land, $\sigma_\theta \simeq 10°$ under neutral conditions; in over-water flows, observed values of σ_θ are typically less than 4° or 5° [Cramer, et al.(1965), Smith and Beesmer (1967), Michael, et al.(1973a,b)]. Such values over land would indicate rather stable conditions but this is not true over water. To see this, one can estimate σ_θ for neutral conditions over the sea from

$$\sigma_{\theta_{neutral}} = \left.\frac{\sigma_v}{u^*}\right|_{neutral} \cdot \frac{k}{\ln\frac{z-d}{z_o}} \qquad (3)$$

For moderate winds z_o is on the order of a few tenths of a mm. With $z \simeq 10$m, the log-law is then rather insensitive to displacement height d, which can be estimated as a meter or so (wave height). Lumley and Panofsky (1964) cite neutral stability values over land of σ_v/u^* varying between 1.3 and 2.6, with larger values originating at rougher sites; Frenzen and Hart (1973) find $\sigma_v/u^* \simeq 1.7$ for neutral conditions over Lake Michigan. For winds of about 10m/sec, then, $\sigma_{\theta_{neutral}}$ may be expected to be between 3° and 5° over the ocean. Evidently Cramer, et al.'s (1964) exponents as functions of σ_θ cannot be expected to directly apply over the sea, since σ_θ will be so much smaller there.

In an attempt to side-step this problem, the exponent p was taken from Table 1 as a function of $\sigma_\theta/\sigma_{\theta_{neutral}}$ (Figure 3); here $\sigma_\theta/\sigma_{\theta_{neutral}}$ serves as an indicator of relative stability. Equations (3) and (10) were used to compute $\sigma_{\theta_{neutral}}$ over the sea as a function of wind speed at 10m (Figure 4), assuming $\sigma_v/u^*_{neutral} \approx 1.3$. By using observed wind speed, one can estimate $\sigma_{\theta_{neutral}}$; this, combined with observed σ_θ, allows formation of the relative stability indicator $\sigma_\theta/\sigma_{\theta_{neutral}}$. The exponent p is then chosen from Figure 3 for use in equation (2). It might be noted that Cramer, et al. (1965) and Smith and Niemann (1969) choose p = 0.8 in their discussions of over-water diffusion.

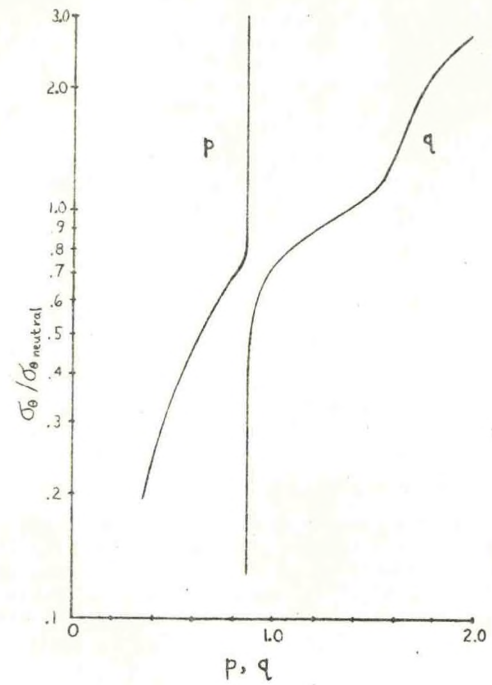

Figure 3. Cramer, et al.'s (1964) exponents as functions of $\sigma_\theta/\sigma_{\theta_{neutral}}$.

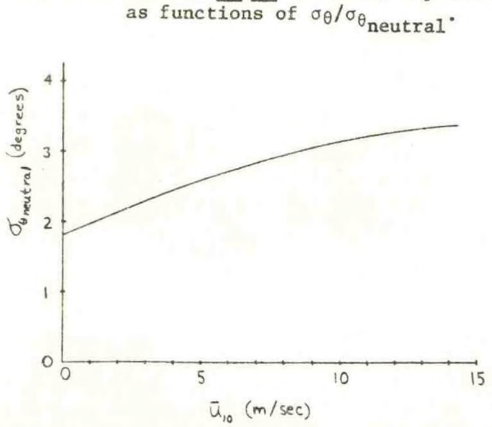

Figure 4. Estimate of $\sigma_{\theta_{neutral}}$ vs. wind speed over the sea.

Islitzer (1961) gives the relation

$$\sigma_y = \frac{\sigma_\theta}{1.23} x . \qquad (4)$$

This equation was deduced from experiments conducted over flat desert terrain in unstable conditions, but has been used by Frenzen and Hart (1973) to estimate σ_y values over Lake Michigan.

Taylor (1921) demonstrated that, for homogeneous isotropic turbulence, an exponential form of the Lagrangian correlation coefficient leads to

$$\sigma_y = \sqrt{At - \frac{A^2}{2(\sigma_\theta\bar{u})^2}\left(1 - \exp\left[-\frac{2(\sigma_\theta\bar{u})^2 t}{A}\right]\right)} , \qquad (5a)$$

where t is travel time. The legitimacy of applying this expression to the atmospheric boundary layer is open to some question [see the discussion following Vaughan (1964)], but, as a practical matter, may be permissible for σ_y, which is less affected by inhomogeneities. Fuquay, et al. (1964) suggest the empirical form

$$A = 13 + 232\ \sigma_\theta\bar{u} . \qquad (5b)$$

Equations (5) have been applied to over-water diffusion by Smith and Beesmer (1967).

When data on the standard deviation of angle of elevation, σ_ϕ are available, Islitzer (1961) recommends $\sigma_z = (\sigma_\phi/1.23)x$. Typically, $\sigma_\phi/\sigma_\theta$ ranges between 0.2 (stable conditions) and 0.7 (unstable) [ASME Guide (1968, 1973)], and so

$$\sigma_z = \frac{\sigma_\theta}{B} x, \qquad (6)$$

where B is a constant of order 5 or so.

Cramer, et al. (1964) suggest

$$\sigma_z \approx \frac{\sigma_\theta}{3} x_r (x/x_r)^q . \qquad (7)$$

Their exponent q is listed for land use in Table 1, and has been plotted as a function of $\sigma_\theta/\sigma_{\theta_{neutral}}$ in Figure 3. Cramer, et al. (1965) indicate that $q \approx 0.35$ for over-water travel at San Nicholas Island, California. Smith and Niemann (1969) found $q \approx 0.45$ for over-water releases at Oceanside, California.

A fairly elaborate scheme for computing σ_z on the basis of local stability and roughness has been set forth by F. B. Smith (1972). Smith gives a "baseline" curve corresponding to neutral, overland stability and roughness length $z_o \approx 10$ cm. An x- dependent stability correction factor is then selected according to local conditions. Adjustment for local roughness is provided by means of another x- dependent correction factor. The technique is extended here to very small z_o. The vertical dispersion coefficient is given by

$$\sigma_z = F(z_o;x) \cdot G(\sigma_\theta;x). \qquad (8)$$

The dimensionless roughness correction factor F (Figure 5) is obtained by extrapolation from Smith's (1972) work. The set of "baseline" curves $G(\sigma_\theta;x)$ correspond to $z_o \approx 10$ cm, and are labeled in Figure 6 according to Slade's (1966) scheme for σ_θ.

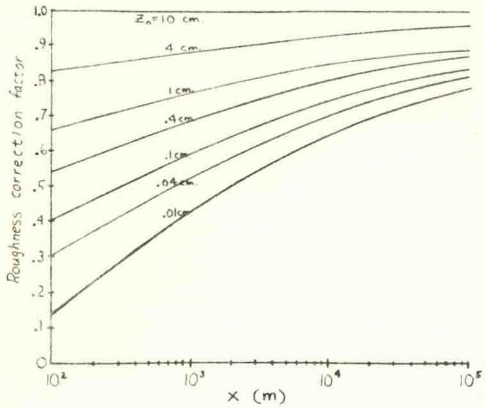

Figure 5. Dimensionless roughness correction factor $F(z_o;x)$ for small values of z_o

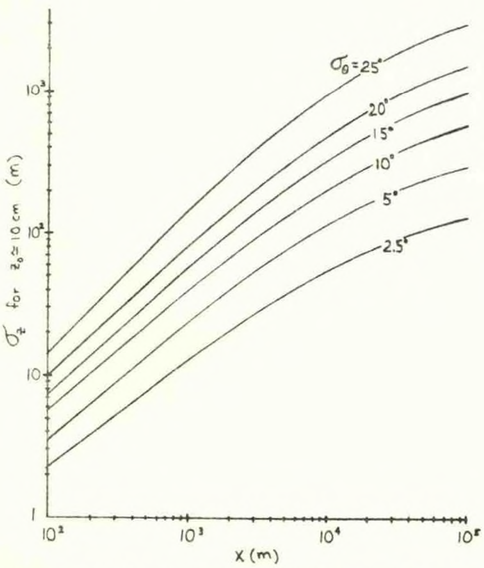

Figure 6. F. B. Smith's (1972) vertical dispersion coefficients for z_o = 10 cm.

To use Smith's method, z_o over the ocean must be estimated. Kitaigorodskii (1973) has hypothesized that z_o depends on the stage of development of the wind-driven waves, as well as on wind speed. Garratt's (1973) work supports this idea. Hence z_o will vary with fetch, wave height and phase velocity, and wind speed and duration. A plot of observations of z_o vs. friction velocity u* alone will therefore show tremendous scatter. A statistical analysis of such a plot by Kitaigorodskii (1973) indicates, however, that z_o (in cm) is described, to at least order of magnitude accuracy, by

$$\bar{z}_o = 0.035\ u^{*2}/g. \qquad (9)$$

The overbar indicates a mean value for the ensemble of all states of wave development possible for a given u*. Equation (9) is within a factor of 3 of that suggested by Charnock (1955). Equation (9) may be combined with the logarithmic velocity profile to obtain z_o as a function of $\bar{u}_{10}$, the mean wind at 10 m (Figure 7). An excellent approximation to this curve is the simple expression

$$z_o \simeq 2 \times 10^{-4}\ \bar{u}_{10}^{\ 2.5}, \qquad (10)$$

with z_o in cm and $\bar{u}_{10}$ in m/sec. Equation (10) is also indicated in Figure 7; it, together with Figures 5 and 6, provides a simple means of estimating $\sigma_z(x)$ through equation (8).

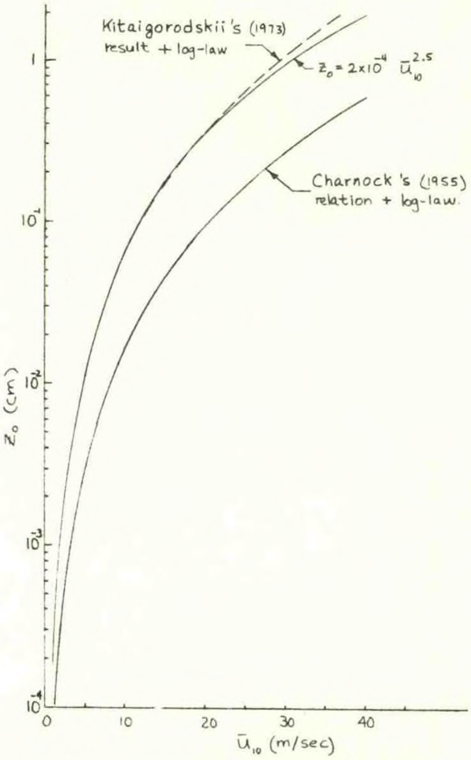

Figure 7. Over-ocean roughness length vs. wind speed by several techniques.

3. COMPARISON WITH DATA

Data from recent over-water oil smoke experiments conducted off Long Island are given in Table 2 [Michael, et al. (1973b), R. M. Brown and S. SethuRaman (private communications)]. Table 3 lists data accumulated from fluorescent particle (FP) releases at Bolsa Island, off California [Smith and Beesmer (1967)].

Table 2

Brookhaven over-water diffusion data [Michael, et al. (1973b), Brown (1974), SethuRaman (1974)]

Run no.	x (m)	$\bar{u}$ @ 16 m (m/sec)	σ_y (m)	$\bar{\chi}_{CL}/Q_0$ (sec/m³)	Time-adjusted† σ_θ (deg)	Time-adjusted† σ_y (m)
2.1	1900	4.8	134	2.8×10^{-5}	3.57	130
2.2	5500	5.9	83.5	1.4×10^{-5}	1.64	74.7
3.2	6700	3.9	66.1	3.3×10^{-5}	~3.56	67.5
4.1	2300	6.06	119	0.68×10^{-5}	4.04	112
4.2	2300	6.06	169	0.46×10^{-5}	4.04	169
6.1*	2600	4.68	93.3	7.13×10^{-5}	~1.5	77.7
6.2*	2600	5.91	96.3	8.95×10^{-5}	2.4	85.6
6.3*	460	4.67	35.5		1.37	35.9
6.4*	930	5.18	62.9		2.48	75.6
6.5*	1840	5.91	75.1		2.40	75.9
7	4300	9.96	53.9	4.56×10^{-5}	1.73	49.7
8.1**	1380	8.36	227	1.52×10^{-5}	8.67	177
8.2**	460	8.36	120	5.74×10^{-5}	8.67	111
9.1	4900	5.7	86.7	2.55×10^{-5}	2.12	78.9
.10	3400	10.8	140	0.189×10^{-5}	2.62	120

*Rainy day.

**Off-shore winds.

† Adj. to time interval of 20 minutes, using $\sigma(T_1) \cong \sigma(T_2)\ [T_1/T_2]^{1/5}$.

Table 3

Bolsa Island over-water diffusion data
[Smith and Beesmer (1967)]

Trial no.	x (m)	$\bar{u}$ @ 16 m (m/sec)	σ_y* (m)	$\bar{\chi}_{CL}$*/Q_0 (sec/m³)	σ_θ* (deg)
1	1300	3.2	100	0.43×10^{-5}	3.5
2	1300	6.8	104	1.05×10^{-5}	2.6
3	1280	9.0	65	1.14×10^{-5}	3.5
5	1310	10.0	90	0.53×10^{-5}	5.3
6	1340	9.6	52	1.25×10^{-5}	3.0
7	1230	5.8	97	1.43×10^{-5}	3.0
8	1250	11.2	47	1.31×10^{-5}	2.3
9	1230	9.6	41	2.30×10^{-5}	2.6

*Time interval of 10 minutes.

In Table 2, since it is was not always possible to obtain σ_θ measurements for the same time and duration as those of σ_y and $\bar{\chi}_{CL}/Q_0$, the values were adjusted to a common averaging time of 20 minutes via the empirical law [Cramer, et al. (1964)]

$$\sigma(t_1) \approx \sigma(t_2) . (t_1/t_2)^{1/5} . \qquad (11)$$

All calculations are made using these adjusted values except for the computation of σ_z, which is evaluated directly from the observed data. Neither data set has been corrected for depletion due to deposition; this may be particularly important for the FP data in Table 3 [Cramer, et al. (1965)], as discussed below.

3.1 Models of σ_y

The parameter σ_y was estimated for the measured values of σ_θ, x, and $\bar{u}$ corresponding to each field trial. Careful interpolation was used with the P.-G. and Briggs curves. The Cramer formulation, equation (2), was applied with several different values for x_r and p. From these estimates, the ratio of predicted to observed σ_y was formed for each trial, and the overall mean and standard deviation of this ratio was computed for each model. The correlation of the individually predicted values of σ_y and the observed σ_y's was also calculated for each model. Examination of preliminary results indicated that the predictability of run 3.2 of Table 2 was very poor. A study of the rough data [R. M. Brown and S. SethuRaman (private communications)] revealed that the wind measurements for that run had been made a few hours before the smoke releases were begun. It seemed quite possible that the character of the wind fluctuations might have changed during that interval, and so run 3.2 was eliminated. The computations were again performed; the results are shown in Table 4.

The Briggs σ_y curves give the best mean value, but also the highest standard deviation (S.D.) and the lowest correlation coefficient.* The Taylor-Fuquay model, on the other hand, is almost as accurate as the Briggs model in predicting the mean, and has the advantage of smaller S. D. and a much better correlation coefficient. Of the ten models considered, five (Briggs, Taylor -Fuquay, P.-G., Islitzer, and Cramer "D") predict the mean within 6%. Of these five, the Cramer "D" model gives by far the smallest S.D. and the highest correlation coefficient. It is also very easy to use. It is interesting that its exponent, p, corresponds to near-neutral conditions over land. The attempts to use stability-adjusted exponents led to high correlation coefficients but considerable underprediction of the mean. Notice that while the Briggs and P.-G. models are both quite accurate in the mean, they both show large S.D.'s (and hence large probable errors) and poor correlation coefficients. Therefore the other models which depend more explicitly on meteorological information are probably preferable.

Table 4

Mean values of ratios of predicted to observed σ_y's, and correlation of predicted to observed σ_y, for several models applied to over-water dispersion*

Model	Type	Mean, pred./obs.	Std. dev., pred./obs.	Corr. coeff., pred. vs obs.	Range (2σ) of corr. coeff.
Pasquill-Gifford	Interpolation between curves	0.957	0.569	0.262	−0.188, 0.621
Briggs (1973)	Interpolation between curves	0.972	0.609	0.213	−0.238, 0.588
Cramer et al. (1964) "A"	$\sigma_y = 100\ \sigma_\theta(x/100)^{.80}$	0.641	0.246	0.736	0.449, 0.885
Cramer et al. (1964) "B"	$\sigma_y = 500\ \sigma_\theta(x/500)^{.80}$	0.884	0.340	0.736	0.449, 0.885
Cramer et al. (1964) "C"	$\sigma_y = 100\ \sigma_\theta(x/100)^{.85}$	0.744	0.303	0.713	0.409, 0.875
Cramer et al. (1964) "D"	$\sigma_y = 500\ \sigma_\theta(x/500)^{.85}$	0.947	0.386	0.712	0.407, 0.874
Cramer et al. (1964) "E"	$\sigma_y = 100\ \sigma_\theta(x/100)^p$	0.679	0.249	0.783	0.533, 0.907
Cramer et al. (1964) "F"	$\sigma_y = 500\ \sigma_\theta(x/500)^p$	0.898	0.322	0.767	0.504, 0.900
Islitzer (1961)	$\sigma_y = (\sigma_\theta/1.23)x$	0.953	0.466	0.630	0.275, 0.834
Taylor (1921); Fuquay et al. (1964)	$\sigma_y = \text{fn}[(x/\bar{u}), \sigma_\theta\bar{u}]$	1.033	0.477	0.613	0.250, 0.825

*Uses all data of Tables 2 and 3, except run 3.2 of Table 2.

3.2 Models of σ_z

Similar computations for σ_z were carried out for each field trial except 3.2 of Table 2. Interpolation was used to read σ_z from the P.-G. and Briggs curves. In the Smith technique, z_0 was estimated from equation (10), and used to interpolate a roughness correction factor from Figure 5; this factor was then applied to the interpolated "baseline" value from Figure 6 to yield a roughness-compensated σ_z. Several variations of the Cramer model, equation (6). were also considered. The experimental data from Tables 2 and 3 were used to compute values of σ_z from equation (1), assuming a sea-level source and taking y = z = 0.

From these numbers, ratios of predicted to "observed"* σ_z's were formed for each field test, and the mean values and S.D. were computed for each model, as were the correlations between

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*Since the data set is small, emphasis should not be placed on the exact value of the correlation coefficient r. Confidence limits (2σ) on r are indicated in Tables 4, 6, and 7; these ranges overlap for many models.

*The quotation marks are used because σ_z is not really observed; it is calculated after a number of assumptions from observed results. Its accuracy is as good as the assumptions.

individual σ_z predictions and "observations". Examination of preliminary results indicated that all the Bolsa Island data were underpredicted, typically by a factor of 2 to 4, even when the predictions of the Brookhaven results were reasonably good. This was particularly true of trial 1 (Table 3) at Bolsa Island, for which σ_z was about 5 times larger than all the other Bolsa Island results, and hence a factor or 10 or more larger than predicted. Smith and Beesmer (1967) also noted this difficulty with trial 1, and discarded it as a "bad" point, though the data they present provide no clear indication as to why this should be so.

Now, as mentioned above, Cramer et al. (1965) suggested the possible importance of deposition with regard to the diffusion of FP above the sea. One can estimate the importance of this phenomenon by incorporating Chamberlain's (1953) definition by deposition velocity v_d into the Gaussian plume [e.g., Van der Hoven (1968)]. The net effect is to replace Q_o in equation (1) by an "effective," source strength $Q(x)$. For a ground-level source, a plume centerline receptor sees the normalized concentration due to the depleting plume as

$$\frac{\bar{\chi}_{CL}}{Q_o} = \frac{Q(x)/Q_o}{\pi \sigma_y \sigma_z \bar{u}} , \qquad (12a)$$

where

$$Q(x)/Q_o = \exp\left[-\sqrt{\frac{2}{\pi}} \frac{v_d}{\bar{u}} \int_o^x \frac{dx}{\sigma_z(x)}\right] . \qquad (12b)$$

Hence

$$\sigma_z = \frac{Q(x)/Q_o}{\pi \bar{u} \sigma_y \frac{\bar{\chi}_{CL}}{Q_o}} \leq \frac{1}{\pi \bar{u} \sigma_y \frac{\bar{\chi}_{CL}}{Q_o}} . \qquad (13)$$

The right side of this inequality is the value calculated from observed data when deposition is ignored; i.e., neglecting deposition leads to over-estimation of experimental σ_z's. To evaluate the degree of over-estimation which may be involved in the Bolsa Island data, the procedure and curves published by Van der Hoven (1968) were used. If a deposition velocity of 8 cm/sec is assumed for FP over water, and the near-neutral ("D") curve of Van der Hoven (1968) is adopted as a conservative approximation for a sea-level source, then the deposition-corrected values of σ_z listed in Table 5 are found. Note that the low wind speed during trial 1 leads to strong plume depletion, thus reducing σ_z for trial 1 to a value quite similar to those obtained for the other Bolsa Island trials. These values are also much more in line with the Brookhaven results, and with the predictions of the various σ_z models. A deposition velocity of 8 cm/sec for FP is large, but not entirely unreasonable; Islitzer and Dumbauld (1961) have cited values ranging between 0.2 cm/sec and 9.2 cm/sec for FP over desert terrain. Furthermore, although data for FP over water could not be found, there is some indication [e.g., see data reviewed by Gifford and Pack (1962)] v_d over water may be larger (perhaps a factor of 2 or so) than over dry surfaces such as sand.

Table 5

Sample results of deposition correction applied to σ's based on Bolsa Island data. Distance $x \cong 1300$ m, deposition velocity $v_d \cong 8$ cm/sec, and near-neutral conditions

Trial no.	Uncorrected σ_z (m)	$\bar{u}$* @ 10 m (m/sec)	$\frac{Q(x)}{Qo}$	Dep.-corrected σ_z (m)
1	231	3.1	0.10	23.1
2	42.9	6.5	0.33	14.2
3	47.7	8.6	0.44	21.0
5	66.7	9.5	0.47	31.3
6	51.0	9.2	0.46	23.5
7	39.6	5.5	0.27	10.7
8	46.2	10.7	0.51	23.6
9	35.2	9.2	0.46	16.2

*Computed by power law $\bar{u}_{10}/\bar{u}_{16} = [10/16]^{0.1}$; Davenport (1965).

Since reliable estimates of v_d for FP over the sea could not be found to permit adjustment of the Bolsa Island results, it was decided to drop that data from further consideration. The deposition velocity of oil smoke on water is unknown, and so no correction could be applied to the Brookhaven data. This effect should probably be investigated in future analyses of these data.

The computations of the ratios of predicted to observed and of the correlation between predicted and observed values were repeated for the Brookhaven data alone; the results are indicated in Table 6.

Table 6

Mean values of ratios of predicted to "observed" σ_z's, and correlation of predicted to "observed" σ_z, for several models applied to over-water dispersion*

Model	Type	Mean, pred./obs.	Std. dev., pred./obs.	Corr. coeff., pred. vs obs.	Range (2σ) of corr. coeff.
Pasquill-Gifford	Interpolation between curves	1.698	1.266	0.239	−0.345, +0.689
Briggs (1973)	Interpolation between curves	1.585	1.272	0.378	−0.202, +0.762
F. B. Smith (1972)	Roughness-corr. interpolation	0.903	0.716	0.514	−0.035, +0.825
Cramer "A"	$\sigma_z = 100(\sigma_\theta/2)(x/100)^{.35}$	0.658	0.742	−0.062	−0.582, +0.494
Cramer "B"	$\sigma_z = 500(\sigma_\theta/2)(x/500)^{.35}$	1.872	2.110	0.062	−0.582, +0.494
Cramer "C"	$\sigma_z = 500(\sigma_\theta/2)(x/500)^{.45}$	2.071	2.158	0.003	−0.537, +0.541
Cramer "D"	$\sigma_z = 100(\sigma_\theta/3)(x/100)^{.95}$	2.329	1.768	0.377	−0.204, +0.761
Cramer "E"	$\sigma_z = 500(\sigma_\theta/3)(x/500)^{9}$	4.440	5.221	0.184	−0.394, +0.658
Cramer "F"	$\sigma_z = (\sigma_\theta/30)x^{1.2}$	1.248	0.882	0.445	−0.124, +0.794
Cramer "G"	$\sigma_z = (\sigma_\theta/80)x^{1.3}$	1.012	0.706	0.447	−0.121, +0.795
Islitzer "A"	$\sigma_z = (\sigma_\theta/3)x$	2.704	2.013	0.401	−0.176, +0.773
Islitzer "B"	$\sigma_z = (\sigma_\theta/8)x$	1.014	0.754	0.400	−0.177, +0.773

*Uses only Brookhaven data (Table 2), except run 3.2.

The Cramer "G" and Islitzer "B" models provide the best mean values, but the Cramer "G" model gives a lower S.D. and somewhat higher correlation coefficient. The exponent of this model is that appropriate for near-neutral conditions over land. The best correlation coefficient is exhibited by the Smith formulation; this model also has a low S.D., and predicts, in the mean, to within about 11%. The P.-G. and Briggs curves seriously overpredict σ_z, have large S.D.'s, and poor correlation with the experimentally derived values. In general, the standard deviations are larger and the correlation coefficients are smaller than for the σ_y models in Table 4, i.e., σ_z seems less predictable than σ_y.

3.3 Models of $\bar{\chi}_{CL}/Q_o$

Four σ_y models (P.-G., Briggs, Cramer "D", Taylor-Fuquay) were selected from Table 4, and used with four σ_z formulations (P.-G., Smith, Cramer "G", Islitzer "B") from Table 6 in the sea-level, center-line version of equation (1) to predict $\bar{\chi}_{CL}/Q_o$. Observed winds from the Brookhaven experiments were used. Again the means and standard deviations of ratios of predicted to observed, and the correlation of individual pairs were examined; the results appear in Table 7.

Table 7

Mean values of ratios of predicted to observed $\bar{\chi}_{CL}/Q_0$'s, and correlation of predicted to observed values, for several models applied to over-water dispersion data from Brookhaven

σ_y model*	σ_z model**	Mean, pred./obs.	Std. dev., pred./obs.	Corr. coeff., pred./obs.	Range (2σ) of corr. coeff.
Taylor-Fuquay	P.-G.	1.146	1.227	0.697	0.253, 0.899
Cramer "D"	P.-G.	1.248	1.343	0.693	0.246, 0.897
P.-G.	P.-G.	1.356	1.390	0.565	0.037, 0.846
Briggs	P.-G.	1.362	1.389	0.540	0.001, 0.836
Taylor-Fuquay	Cramer "G"	1.695	1.499	0.659	0.186, 0.884
Taylor-Fuquay	Islitzer "B"	1.756	1.643	0.694	0.247, 0.897
Cramer "D"	Cramer "G"	1.824	1.611	0.686	0.233, 0.894
Taylor-Fuquay	Smith	1.895	1.577	0.671	0.207, 0.889
Cramer "D"	Islitzer "B"	1.909	1.786	0.686	0.234, 0.894
Cramer "D"	Smith	2.074	1.726	0.655	0.179, 0.883
P.-G.	Cramer "G"	2.098	1.875	0.484	−0.075, 0.811
P.-G.	Islitzer "B"	2.098	1.944	0.602	0.093, 0.862
Briggs	Islitzer "B"	2.107	1.950	0.581	0.061, 0.853
Briggs	Cramer "G"	2.111	1.891	0.467	−0.096, 0.804
P.-G.	Smith	2.228	1.872	0.642	0.157, 0.877
Briggs	Smith	2.236	1.885	0.624	0.128, 0.870

*Definitions from Table 4.
**Definitions from Table 6.

The combination of the Taylor-Fuquay expression for σ_y [equations (5)], and σ_z as read from the P.-G curves [Slade (1968)] gives the best mean value, lowest standard deviation, and highest correlation coefficient of all the combinations tested. All the models overpredict in the mean, some by a factor of 2 or more, and all exhibit quite large S.D.'s; roughly speaking, the standard deviation increases with the degree of mean overprediction.

4. SUMMARY AND CONCLUSIONS

It has been found that five models can predict σ_y, in the mean, to within about 6%, and with reasonable accuracy (factor of 2 or better, generally) for individual points. The best of these models is that suggested by Taylor (1921) and Fuquay, et al. (1964), and expressed in equations (5). The Pasquill-Gifford curves provide good accuracy in the mean, but the confidence limits of their predictions are somewhat larger.

Only three models can predict σ_z, in the mean, within 11%, and the accuracy for individual predictions is rather poor (factor of 3 or worse). Part of the difficulty may be related to the problem of accurately determining experimental values of σ_z. Indirect evaluations, such as performed above, are subject to substantial errors introduced by deposition. It would be most helpful to have direct measurements of σ_z in future experiments. Deposition estimates should also be reported whenever possible.

The combination of the Taylor-Fuquay expression for σ_y and the Pasquill-Gifford curves for σ_z provides estimates of $\bar{\chi}_{CL}/Q_o$, in the mean, to about 15%, but the confidence limits on individual predictions are rather larger (factor of 4 or so). Other model combinations provide worse prediction in the mean, coupled with larger probable errors.

On the whole, the use of observed $\bar{u}$ and σ_θ seems to provide sufficient information for adequate estimates of lateral diffusion. Prediction of the vertical diffusion and of the centerline concentration is not as satisfactory, but may be acceptable. It should be remarked that these results are largely based on analysis of a rather small data set from a single ocean site, and are subject to revision as more data becomes available. In the meantime, estimation of over-water diffusion should continue to be approached with caution.

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