The Long Lifetime of the Dispersion Methods of Pasquill in U.S. Regulatory Air Modeling

D. BRUCE TURNER

Trinity Consultants, Incorporated, Chapel Hill, North Carolina

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ABSTRACT

The suggestions of Pasquill as set forth in his landmark 1961 *Meteorological Magazine* paper are briefly reviewed. These methods are viewed from the perspective of the requirements placed upon air agencies after the passage of the Clean Air Act in 1970. Pasquill's clarification of the use of his methods in a technical report for the Environmental Protection Agency (EPA) is discussed in relation to the incorporation of these methods into numerous air quality dispersion models. The shifts in the problem areas faced by the EPA and the relation of these to the methods of Pasquill are discussed. Reasons are suggested for the long persistence of the Pasquill methods in the models used to address U.S. EPA regulations. Current trends in the incorporation of newer techniques into regulatory modeling and their relation to the methods of Pasquill are briefly stated.

1. Introduction

The material that appeared in the 1961 article "The Estimation of the Dispersion of Windborne Material" by Pasquill was circulated among a number of meteorologists interested in air pollution and dispersion quite some time prior to its publication. Pasquill indicated that the results of investigations at Porton, which were also supported by experimental studies in the United States, "form the basis for a tentative system of estimating diffusion in a wide range of meteorological conditions and over distances up to about 100 kilometres." He stated that the purpose of his paper was "to review the recent background of theoretical and experimental results, and to give details of the proposed system of calculating the distribution of concentration downwind of a source."

2. The suggestions of Pasquill

Pasquill pointed out that the analysis of Taylor (1921) assumed homogeneous and steady fields of turbulence. This is not generally the case; for example, "near the ground the structure of turbulence changes systematically with height." Pasquill then stated, "However, subject to certain restrictions, it is not unreasonable to assume the existence of *quasi*-homogeneous, *quasi*-steady properties in the horizontal plane, and even in the vertical plane well away from the ground." The restrictions that he mentioned are those due to topography; short enough time periods should also be considered so that significant temporal changes do not occur. A simple adaptation of Taylor's treatment was developed by Hay and Pasquill (1959) using an assumption about the ratio β of the timescales of the Lagrangian to the Eulerian autocorrelation coefficient of eddy velocity.

Estimates of the horizontal dispersion for given time intervals for releases from continuous sources can be made from standard deviations calculated from averages of the wind direction over moving time intervals.

Specifically, the crosswind dispersion for a time period τ can be estimated by averaging the wind direction θ over moving time intervals of duration $x/(u\beta)$ and using the following relation:

$$\frac{\sigma_y}{x} \approx [\sigma_\theta]_{\tau, x/u\beta}. \quad (1)$$

The σ_θ is in radians. From a limited number of field measurements, Hay and Pasquill (1959) estimated β to be about 4. The implication is that this technique can be expected to be useful for releases from any height.

With regard to vertical dispersion from releases near the ground, Pasquill cited the work of Calder (1949) and Monin (1959) and the summarization of the Prairie Grass, Nebraska, measurements by Cramer (1957) as being useful. For elevated releases, an analysis of the elevation angle of the wind ϕ can be made, similar to the analysis of the wind direction for horizontal dispersion. The equation used is

$$\frac{\sigma_z}{x} \approx [\sigma_\phi]_{\tau, x/u\beta}, \quad (2)$$

where, as for Eq. (1), values of vertical dispersion over

Corresponding author address: D. Bruce Turner, Trinity Consultants, Inc., P.O. Box 2099, Chapel Hill, NC 27515-2099.

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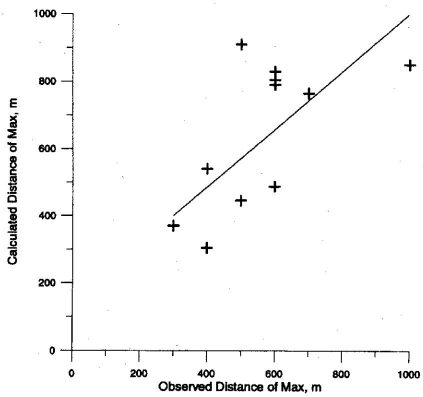

FIG. 1. Distance to the ground-level maximum concentration from a 50-m source calculated using fluctuation statistics compared to the distance to the maximum concentration observed from tracer measurements. Data from Pasquill's (1961) Table 1.

time τ are determined by averaging values of ϕ in radians over moving time intervals of duration $x/(u\beta)$ prior to the calculation of σ_ϕ.

The usefulness of these equations was verified using the results of 13 tests made at the National Reactor Testing Site at Idaho Falls, Idaho. Wind fluctuations were measured along with a release of a tracer from a height of 50 m. Ground-level concentration measurements were made on arcs that were each 100 m from the release point. Ground-level concentration estimates were made using wind fluctuation statistics. Figure 1 shows a comparison of the observed distance of the maximum as shown by the tracer concentrations with the calculated distance of the maximum obtained from the estimates made from the fluctuation statistics. These values are given in Pasquill's (1961) Table 1. The correlation coefficient of 0.7 shows the relation to be quite good.

Additionally, tracer samples collected from sampling units mounted on the cable of a barrage balloon about 50 miles downwind from a crosswind line source at about 1000-ft height also confirmed the usefulness of Eq. (2).

As a practical example, it can be noted that for an existing wind speed of 5 m s^{-1}, averaging of θ and ϕ over time intervals of 5, 10, 50, and 100 s throughout a 1-h time period can be used to estimate the dispersion for this hour at distances of 100, 200, 1000, and 2000 m downwind.

In setting up a "practical system for estimating the concentration or dosage pattern up to about 100 kilometres from a source," Pasquill referred to the angular crosswind spreading of the pollutant plume as θ. This includes both sides of the plume to the edges, where the concentrations drop to 10% of the plume centerline concentration. Thus, the arc distance included in the angle θ is approximately equivalent to $4.3\sigma_y$. For the vertical dispersion, he used the height h to refer to the height above the ground where the concentrations drop to 10% of those at plume centerline. For a ground-level source, his h would be equivalent to $2.15\sigma_z$.

In introducing this "practical system" Pasquill again stated, "When the necessary special data on wind fluctuation are available, θ should be calculated from equation (1). Likewise, it is recommended that h be calculated from equation (2), using data on the fluctuation of the wind inclination well clear of the ground, except for short distances (say <1 km) from a ground-level source."

Several other clarifications were made.

- "The estimates of θ tabulated on Figure 2 [Pasquill's Fig. 2] are for a *short* release (a few minutes) and are based on recently acquired statistics of wind direction fluctuation."
- "It should also be emphasized that the estimates of θ and h are appropriate to fairly level open country. In an urban area, or on an industrial site, there will be additional dynamical turbulence generated by the buildings, and this may be expected to increase the spread of the plume."
- "It is emphasized that the present system can in general give only very approximate estimates of the magnitudes of the concentrations, especially when it is necessary to use the tentative statistical estimates of h and θ."

Where fluctuation statistics were not available, the practical system consisted of a table to estimate stability class and a graph of h, for each of six classes, related to source–receptor downwind distance (Pasquill's Fig. 2), with a table superimposed on the graph giving values of θ for the stability classes at two distances, 0.1 and 100 km. The stability class table determines daytime stability from wind speed at 10 m and insolation (incoming solar radiation). The nighttime stability is determined from wind speed at 10 m and cloud cover.

Gifford (1961), having been sent a draft of the Pasquill (1961) paper, converted values of Pasquill's h to values of σ_z and values of Pasquill's θ to values of σ_y, which he displayed as curves for each stability on log–log plots of dispersion parameter as a function of downwind distance from the source. The transformation by Gifford is how these dispersion parameters came to be known as Pasquill–Gifford (P–G) parameters.

Pasquill (1961) and Gifford (1961) were summarized by Turner (1967) who added graphs, tables, and example problems with solutions. This assisted in making dispersion estimates easier in the days prior to the availability of the hand-held calculator. A second edition of this workbook (Turner 1994), which includes a floppy diskette, allows the use of a personal computer to explore the sensitivity of estimated concentrations to changes in various input parameter values.

3. Perspective on the methods

To those of us working in the field of air pollution meteorology, it was natural to assume that the position taken by Pasquill with the publication of this paper would provide the impetus and encouragement for those concerned with air pollution problems or control to *make measurements of wind fluctuation* and to make use of these in making source impact assessments.

It was also obvious that widespread establishment of the required wind systems would not take place overnight and that considerable use of the approximation techniques would be made in the interim. However, it has been quite surprising that this "interim" has dragged on from 1961 to the present day.

4. Air pollution problems initially faced by the Environmental Protection Agency and its predecessors

Initially, as a federal air pollution program got underway in the United States, air pollution was recognized as primarily an urban problem, and air quality measurement programs were undertaken in Nashville, Tennessee, and in Louisville, Kentucky. It was recognized that many sources were contributing to the pollutant concentration levels. However, it was also noted that when high short-term concentrations of a few hours were occurring, quite significant contributions were probably coming from large emitters with significant stack heights. These studies then indicated that to solve the nation's air pollution problems, reduction of emissions from all types of sources would be required. However, uniform reduction, or rollback, would not be required, as all sources were not contributing in proportion to their emissions, primarily due to the heights of the various emissions.

5. Pasquill's clarification of his methods

In 1976, Pasquill had an extended working visit to the United States. During that visit, he prepared comments (Pasquill 1976) clarifying what was contained in his 1961 paper and making suggestions for the improvement of the general procedures. He indicated that the estimates of the crosswind spreading for "a *short* release (a few minutes)" referred to 3 min.

He also stated, "However, in the absence of strong evidence or argument to the contrary, acceptance of the estimates even for elevated releases (in more general terms for $H \geq \sigma_z$) was encouraged."

Pasquill summarized the basis and scope of the original P–G curves. Regarding the crosswind spread, they were for any source height within the mixed layer for sampling times of 3 min. The basis for the values of 0.1–1 km was "preliminary statistics of wind direction fluctuation for a surface roughness, z_o, equal to 3 cm." The basis for 10–100 km was "extrapolation of short-range data in the light of limited special observations of tracer dispersion over level terrain of mixed roughness (implied z_o = 30 cm)."

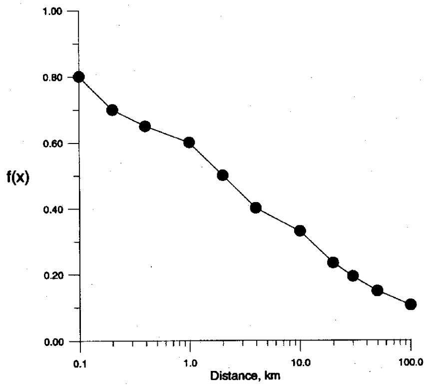

FIG. 2. Pasquill's (1976) function $f(x)$ as a function of the downwind distance x.

The vertical spreading values were for a surface release, but were usable for any height in a mixed layer in the absence of strong evidence against doing so. They were for any sampling time, but most applicable to roughly 10 min. The basis for 0.1–1 km was "properties of the wind profile over a surface of small roughness (z_o = 3 cm), with guidance from dispersion studies especially as regards effect of thermal stratification." The basis for 10–100 km was "as for σ_y, with guidance from early data on the properties of the vertical component of turbulence at heights throughout the mixed layer."

Pasquill recommended interim changes in the use of the P–G dispersion parameters. For crosswind spread, "irrespective of the terrain roughness, release height and sampling duration up to about 1 hour, use the formula:

$$\frac{\sigma_y}{x} = \sigma_\theta f(x)'', \tag{3}$$

where σ_θ (rad) is the best available estimate of the standard deviation of the wind direction fluctuation for the sampling time of interest and for the height at which u is specified. The σ_θ "should be for an effectively infinitesimal averaging time." That is, there is no smoothing of the data before calculating σ_θ. The $f(x)$ decreases from a value of 1 at the source to lower values at greater distances. Pasquill gave values of this function in tabular form, with a few values as follows: 0.8 at 0.1 km, 0.6 at 1 km, and 0.33 at 10 km. Figure 2 is a plot of $f(x)$ with distance x from the source. Equations for $f(x)$ are

$$f(x) = \begin{cases} 1.0, & x \leq 0.014 \text{ km} \quad (4) \\ -0.238 \log_{10}x + 0.559, & x > 0.014 \text{ km}. \quad (5) \end{cases}$$

This function accounts for the wide deviations of the wind from the mean that cause dispersion effects for only short times and, therefore, affect only close-in receptors.

A second recommendation regarding crosswind spread is the inclusion at distances greater than or equal to 20 km of additional spread due to vertical wind direction shear moving the top and bottom of the plume in different directions. The suggestion is to calculate $0.03(\Delta\theta)^2x^2$, "where $\Delta\theta$ is the turning of wind direction over the total depth of the plume, in radians." This value is added to the square of σ_y determined above and the square root taken of the result—that is, adding variances.

For vertical spread, the σ_z values can be used "for any sampling time for a surface release, and greater than 10 minutes for an elevated release with the following adjustments:"

1) "For terrain with z_o different from 3 cm apply factors based on F. B. Smith's (Smith 1973) nomogram";
2) "To allow for 'urban heating' adopt a stability category one-half category more unstable than that prescribed in the normal way";
3) "For evaluating the concentration at the surface from a surface release, consider estimates of the effective mixed depth h' at the mid-time of sampling, recognizing especially its growth from very small values on stable nights, and then adopt either σ_z as given by the curves, or 0.8 h', whichever is the smaller"; and
4) "For buoyant plumes, increase the σ_z^2 obtained from the curves by adding $\Delta H^2/10$ where ΔH is the estimated plume rise."

Reactions to the 1976 recommendations. Neither of the crosswind spreading suggestions were adopted. This is probably due to the lack of necessary information on σ_θ and wind direction shear between the top and bottom of plumes from routinely available meteorological data. With regard to vertical spreading, no changes for roughness were made, and Briggs's urban parameters (Gifford 1976) were adopted for urban conditions.

The only suggestion made that was adopted by the U.S. Environmental Protection Agency (EPA) for routine modeling use was that for the initial size for buoyant plumes, generally referred to as "buoyancy-induced dispersion."

6. Inferred reasons for the long persistence of the methods

Why has the backup method of dispersion estimates been in use so long? The principal reason is probably the lack of fluctuation statistics from routinely collected meteorological data. Fluctuation statistics have been available only from specially set up measurement programs. The EPA is responsible for regulating thousands of sources, and since it is not reasonable for each source having an on-site meteorological program of measurements, no requirements for meteorological measurements were placed upon *any* source.

The use of the current procedure of dispersion estimation, that of classifying the stability and accessing either rural or urban dispersion parameters as functions only of stability class and downwind distance from source to receptor, which has been referred to here as the "backup method," has been shown through various evaluations to give reasonable concentration estimates for most regulatory purposes. Those requirements, in general, are to estimate statistically rare events such as second high values once a year without any regard to specific location or specific time of occurrence. In addition, by using the current techniques, everyone applies the models in the same manner using the same data and gets the same answers.

Requiring the use of only routinely collected data may have allowed arguments to be avoided for many years that could have arisen if onsite data were more generally used. Such things as representativeness of measurements, height of measurements, responsiveness of sensors, and manner of electronically processing data would all be subjects of technical judgement and possible disagreement.

Avoiding decisions as to which sources would be required to have onsite measurement programs, the reasonableness of the resulting concentration estimates from the backup method, and avoiding arguments on technical judgement related to onsite measurements may all have been reasons for keeping in use simple, easily applied techniques that give reasonable answers.

7. What is on the horizon?

A new American Meteorological Society–Environmental Protection Agency (AMS–EPA) Regulatory Model [AERMOD; AMS–EPA Regulatory Model Improvement Committee (AERMIC) Model] (Perry et al. 1994) became available from the SCRAM bulletin board for examination and comment in July 1995. This model is the product of considerable work by AERMIC. The model incorporates the suggestions of many to include what is considered the present-day state of science in modeling. Features suggested by Gryning et al. (1987) and Weil (1988), and features included in the Hybrid Plume Dispersion Model (Hanna and Paine 1989) have been incorporated.

Currently, most models require a minimum of specific meteorological information and are set up to use only that specific set of data. The meteorological processor AERMET, which supports AERMOD, differs in that a variety of information beyond the minimum can be entered and is used. If only a minimum of information is available, vertical profiles of turbulence, wind, and temperature are generated through surface and mixed layer scaling. If any of the vertical profiles are furnished as input, they are used directly.

Plume growth is calculated as a function of turbulence level, height of release, and the vertical structures of both temperature and velocity. The meteorological variables that affect plume dispersion are generated as averages over the appropriate depth of the boundary layer. Mixed-layer heights are calculated from boundary layer models that use available observations and a surface energy balance. Updated plume rise formulations have explicit treatments of the effects of convective turbulence and partial plume penetration. To treat terrain effects, the concept of dividing streamline height is used to result in a consistent treatment of receptors above and below stack height.

Non-Gaussian vertical distributions that result from convective situations and from surface releases are included. Under extreme convective conditions, thermals occupy about one-third of the area above the surface with upward vertical velocities of up to 2 m s^{-1}, and the remaining two-thirds of the area has decending air returning to the surface with maximum downward velocities on the order of 1 m s^{-1}. This results in a skewed distribution of vertical velocities with more downward motions of small magnitudes and few upward motions, but which are of larger magnitude. The AERMOD considers this probability density function of vertical velocities and makes estimates of the resulting non-Gaussian vertical distribution of concentrations. For surface releases, the features of the rapidly changing wind speed profile and the changing turbulence eddy structure, from small-eddy dominance near the surface to the inclusion of larger eddies at higher heights, which affect the vertical concentration distribution, are handled by separate treatment in the model.

Something that has required considerable work, but is transparent to the users, is that smooth transitions are made from one model regime to another so that no sudden changes in concentration result with slight changes in input parameter values. Developmental evaluation is nearing completion using five databases. This is a diagnostic evaluation to identify and correct problems in the model, and it has resulted in a number of revisions (Cimorelli et al. 1996). The resulting model will be subjected to further evaluation using independent datasets. It would appear that AERMOD has the potential of providing very useful technology to air quality simulation modelers and is likely to be specified in future regulatory model guidance.

8. Conclusions

The backup procedures for estimating atmospheric dispersion suggested by Pasquill (1961) have had a long and useful lifetime. Now it appears that we soon will be moving on to the use of improved procedures, including the primary suggestions in Pasquill's 1961 paper, for making estimates of dispersion from turbulent fluctuation statistics.

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