21

Transport and Dispersion of Air Pollutants

I. WIND VELOCITY

A. Wind Direction

The initial direction of transport of pollutants from their source is determined by the wind direction at the source. Air pollutant concentrations from point sources are probably more sensitive to wind direction than any other parameter. If the wind is blowing directly toward a receptor (a location receiving transported pollutants), a shift in direction of as little as 5° (the approximate accuracy of a wind direction measurement) causes concentrations at the receptor to drop about 10% under unstable conditions, about 50% under neutral conditions, and about 90% under stable conditions. The direction of plume transport is very important in source impact assessment where there are sensitive receptors or two or more sources and in trying to assess the performance of a model through comparison of measured air quality with model estimates.

There is normally considerable wind direction shear (change of direction) with height, especially near the ground. Although surface friction causes the wind to shift clockwise (veer) with height near the ground, the horizontal thermal structure of the atmosphere may exert a dominating influence at

higher altitudes, such that the wind will shift counterclockwise (back) with additional height. Cold air advection in an air layer will cause the wind to back with height through that layer. Warm air advection will cause veering with height.

B. Wind Speed

Wind speed generally increases with height. A number of expressions describe the variation of wind speed in the surface boundary layer. A power law profile has frequently been used in air pollution work:

$$u(z) = u(z_a)(z/z_a)^p \tag{21.1}$$

where $u(z)$ is the wind speed at height z, $u(z_a)$ the wind speed at the anemometer measurement height z_a, and p an exponent varying from about 0.1 to 0.4. Figure 21.1 gives the measured wind speed variation with height for specific instances for five locations. The result of using the power law profile (Eq. 21.1) is also shown (open circles and dashed lines) using a value of p of 1/7. It should be noted that the power law wind profiles do not necessarily represent the data well. The exponent actually varies with atmospheric stability, surface roughness, and depth of the layer [1].

One of the effects of wind speed is to dilute continuously released pollutants at the point of emission. Whether a source is at the surface or elevated, this dilution takes place in the direction of plume transport. Figure 21.2 shows this effect of wind speed for an elevated source with an emission of

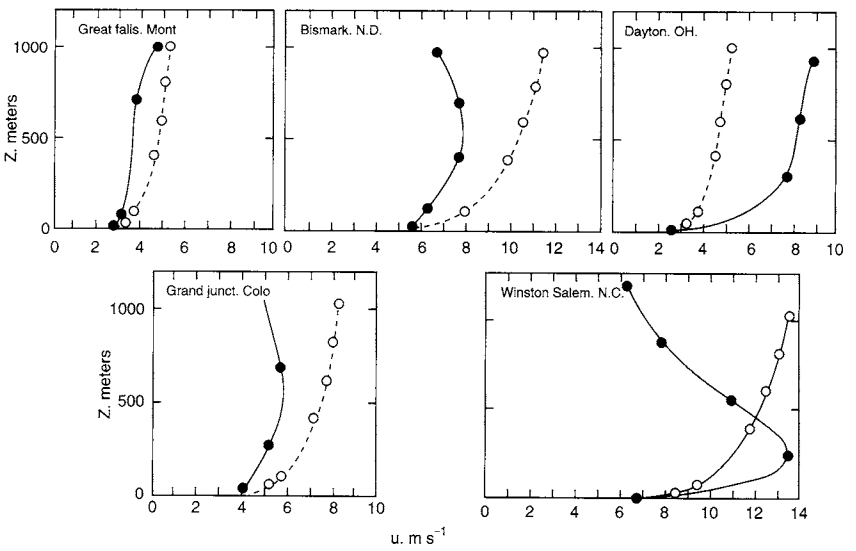


Fig. 21.1. Wind variation with height—measured (solid lines) and one-seventh power law (dashed lines).

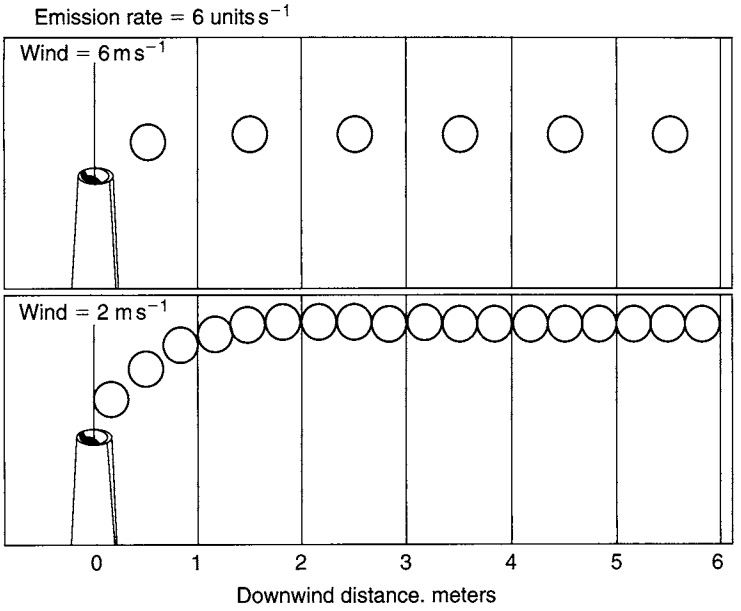


Fig. 21.2. Dilution by wind speed.

6 mass units per second. For a wind speed of 6 m s^{-1}, there is 1 unit between the vertical parallel planes 1 m apart. When the wind is slowed to 2 m s^{-1}, there are 3 units between those same vertical parallel planes 1 m apart. Note that this dilution by the wind takes place at the point of emission. Because of this, wind speeds used in estimating plume dispersion are generally estimated at stack top.

Wind speed also affects the travel time from source to receptor; halving of the wind speed will double the travel time. For buoyant sources, plume rise is affected by wind speed; the stronger the wind, the lower the plume. Specific equations for estimating plume rise are presented in Chapter 22.

II. TURBULENCE

Turbulence is highly irregular motion of the wind. The atmosphere does not flow smoothly but has seemingly random, rapidly varying erratic motions. This uneven flow superimposed on the mean flow has swirls or eddies in a wide range of sizes. The energy cascades through the eddy sizes, which are described by L. F. Richardson in verse:

> Big whirls have little whirls that feed on their velocity
> And little whirls have lesser whirls and so on to viscosity.

There are basically two different causes of turbulent eddies. Eddies set in motion by air moving past objects are the result of mechanical turbulence. Parcels of superheated air rising from the heated earth's surface, and the slower descent of a larger portion of the atmosphere surrounding these more rapidly rising parcels, result in thermal turbulence. The size and, hence, the scale of the eddies caused by thermal turbulence are larger than those of the eddies caused by mechanical turbulence.

The manifestation of turbulent eddies is gustiness and is displayed in the fluctuations seen on a continuous record of wind or temperature. Figure 21.3 displays wind direction traces during (a) mechanical and (b) thermal turbulence. Fluctuations due to mechanical turbulence tend to be quite regular; that is, eddies of nearly constant size are generated. The eddies generated by thermal turbulence are both larger and more variable in size than those due to mechanical turbulence.

The most important mixing process in the atmosphere which causes the dispersion of air pollutants is called *eddy diffusion*. The atmospheric eddies cause a breaking apart of atmospheric parcels which mixes polluted air with relatively unpolluted air, causing polluted air at lower and lower concentrations to occupy successively larger volumes of air. Eddy or turbulent dispersion is most efficient when the scale of the eddy is similar to that of the pollutant puff or plume being diluted. Smaller eddies are effective only at tearing at the edges of the pollutant mass. On the other hand, larger eddies will usually only transport the mass of polluted air as a whole.

The size and influence of eddies on the vertical expansion of continuous plumes have been related to vertical temperature structure [3]. Three appearances of instantaneous plumes related to specific lapse rates and three appearances of instantaneous plumes related to combinations of lapse rates are shown in Fig. 21.4. Strong lapse is decrease of temperature with height in excess of the adiabatic lapse rate. Weak lapse is decrease of temperature with height at a rate between the dry adiabatic rate and the isothermal condition (no change of temperature with height).

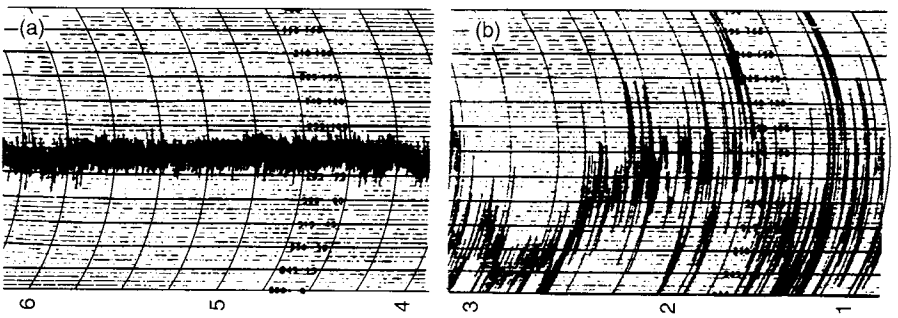


Fig. 21.3. Examples of turbulence on wind direction records: (a) mechanical and (b) thermal. *Source*: From Smith [2].

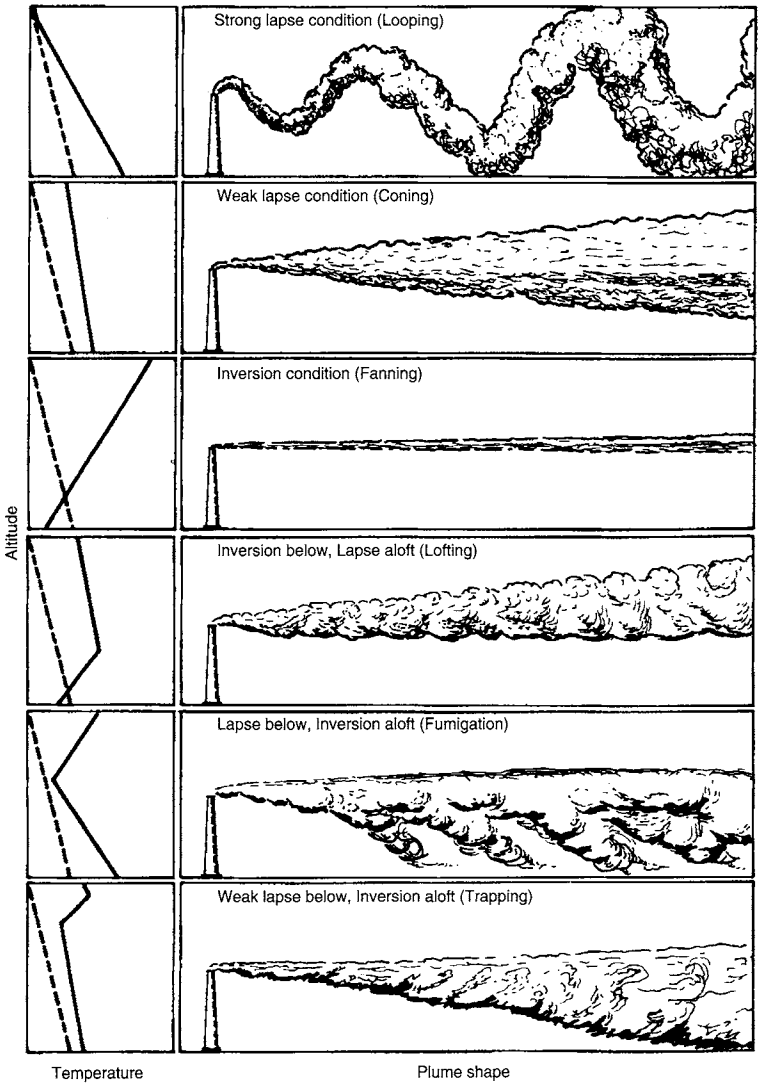


Fig. 21.4. Vertical expansion of continuous plumes related to vertical temperature structure. The dashed lines correspond to the dry adiabatic lapse rate for reference.

A number of methods have been used to measure or estimate the level of turbulence in the atmosphere and, in turn, its dispersive ability. These methods vary from direct measurement of wind fluctuations by sensitive wind measurement systems; to classification based on the appearance of the chart record of the wind direction trace; to classification of atmospheric stability indirectly by wind speed and estimates of insolation (incoming solar radiation) or outgoing longwave radiation. Details of these methods are given in the next section.

III. ESTIMATING CONCENTRATIONS FROM POINT SOURCES

The principal framework of empirical equations which form a basis for estimating concentrations from point sources is commonly referred to as the *Gaussian plume model*. Employing a three-dimensional axis system of downwind, crosswind, and vertical with the origin at the ground, it assumes that concentrations from a continuously emitting plume are proportional to the emission rate, that these concentrations are diluted by the wind at the point of emission at a rate inversely proportional to the wind speed, and that the time-averaged (about 1 h) pollutant concentrations crosswind and vertically near the source are well described by Gaussian or normal (bell-shaped) distributions. The standard deviations of plume concentration in these two directions are empirically related to the levels of turbulence in the atmosphere and increase with distance from the source.

In its simplest form, the Gaussian model assumes that the pollutant does not undergo chemical reactions or other removal processes in traveling away from the source and that pollutant material reaching the ground or the top of the mixing height as the plume grows is eddy-reflected back toward the plume centerline.

A. The Gaussian Equations

All three of the Gaussian equations (21.2 through 21.4) are based on a coordinate scheme with the origin at the ground, x downwind from the source, y crosswind, and z vertical. The normal vertical distribution near the source is modified at greater downwind distances by eddy reflection at the ground and, when the mixing height is low, by eddy reflection at the mixing height. *Eddy reflection* refers to the movement away ("reflection") of circular eddies of air from the earth's surface, since they cannot penetrate that surface. Cross sections in the horizontal and vertical at two downwind distances through a plume from a 20-m-high source with an additional 20 m of plume rise (to result in a 40-m effective height) are shown in Fig. 21.5. The following symbols are used:

- X concentration, g m^{-3}
- Q emission rate, g s^{-1}
- u wind speed, m s^{-1}
- σ_y standard deviation of horizontal distribution of plume concentration (evaluated at the downwind distance x and for the appropriate stability), m
- σ_z standard deviation of vertical distribution of plume concentration (evaluated at the downwind distance x and for the appropriate stability), m
- L mixing height, m
- h physical stack height, m

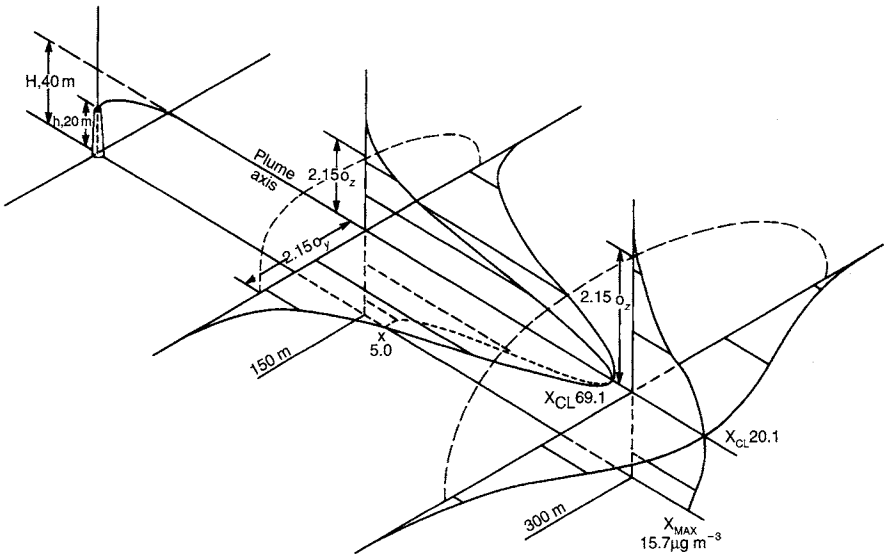


Fig. 21.5. Two cross sections through a Gaussian plume (total mass under curves conserved).

H effective height of emission, m
x downwind distance, m
y crosswind distance, m
z receptor height above ground, m

The concentration χ resulting at a receptor at (x, y, z) from a point source located at $(0, 0, H)$ is given by one of the three following equations. (Methods for obtaining values for the dispersion parameters σ_y and σ_z in the following equations are discussed later in this chapter.)

For stable conditions or unlimited vertical mixing (a very high mixing height), use

$$\chi = Q(1/u)\{g_1/[(2\pi)^{0.5}\,\sigma_y]\}\{g_2/[(2\pi)^{0.5}\,\sigma_z]\} \tag{21.2}$$

where

$$g_1 = \exp\left(-0.5y^2/\sigma_y^2\right)$$
$$g_2 = \exp\left[-0.5\,(H-z)^2/\sigma_z^2\right] + \exp\left[-0.5\,(H+z)^2/\sigma_z^2\right]$$

Note that if $y = 0$, or $z = 0$, or both z and H are 0, this equation is greatly simplified. For locations in the vertical plane containing the plume centerline, $y = 0$ and $g_1 = 1$.

For unstable or neutral conditions, where σ_z is greater than $1.6L$, use

$$\chi = Q(1/u)\{g_1/[(2\pi)^{0.5}\,\sigma_y]\}(1/L) \tag{21.3}$$

For these large σ_z values, eddy reflection has occurred repeatedly both at the ground and at the mixing height, so that the vertical expanse of the plume has been uniformly mixed through the mixing height, i.e., $1/L$.

For unstable or neutral conditions, where σ_z is less than $1.6L$, use the following equation provided that both H and z are less than L:

$$\chi = Q(1/u)\{g_1/[(2\pi)^{0.5}\,\sigma_y]\}\{g_3/[(2\pi)^{0.5}\,\sigma_z]\} \tag{21.4}$$

where

$$g_3 = \sum_{N=-\infty}^{\infty} \{\exp[-0.5(H - z + 2NL)^2/\sigma_z^2] + \exp[-0.5(H + z + 2NL)^2/\sigma_z^2]\}$$

This infinite series converges rapidly, and evaluation with N varying from -4 to $+4$ is usually sufficient. These equations are used when evaluating by computer, as the series g_3 can easily be evaluated.

When estimates are being made by hand calculations, Eq. (21.2) is frequently applied until $\sigma_z = 0.8L$. This will cause an inflection point in a plot of concentrations with distance.

By adding Eq. (21.4), which includes multiple eddy reflections, and changing the criteria for the use of Eq. (21.3) to situations in which σ_z is evaluated as being greater than $1.6L$, a smooth transition to uniform mixing, Eq. (21.3), is achieved regardless of source or receptor height. By differentiating Eq. (21.2) and setting it equal to zero, an equation for maximum concentration can be derived:

$$\chi_{\max} = \frac{2Q}{\pi u e H^2}\frac{\sigma_z}{\sigma_y} \tag{21.5}$$

and the distance to maximum concentration is at the distance where $\sigma_z = H/(2)^{0.5}$. This equation is strictly correct only if the σ_z/σ_y ratio is constant with distance.

B. Alternate Coordinate Systems for the Gaussian Equations

For estimating concentrations from more than one source, it is convenient to use map coordinates for locations. Gifford [4] has pointed out that the resulting calculated concentration is the same whether the preceding axis system is used or whether an origin is placed at the ground beneath the receptor, with the x-axis oriented upwind, the z-axis remaining vertical, and the y-axis crosswind.

This latter axis system is convenient in assessing the total concentration at a receptor from more than one source provided that the wind direction can be assumed to be the same over the area containing the receptor and the sources of interest.

Given an east–north coordinate system (R, S) the upward distance x and the crosswind distance y of a point source from a receptor are given by

$$x = (S_p - S_r)\cos\theta + (R_p - R_r)\sin\theta \tag{21.6}$$

$$y = (S_p - S_r)\sin\theta - (R_p - R_r)\cos\theta \tag{21.7}$$

where R_p, S_p are the coordinates of the point source; R_r, S_r are the coordinates of the receptor; and θ is the wind direction (the direction from which the wind blows). The units of x and y will be the same as those of the coordinate system R, S. In order to determine plume dispersion parameters, distances must be in kilometers or meters. A conversion may be required to convert x and y above to the appropriate units.

C. Determination of Dispersion Parameters

1. *By Direct Measurements of Wind Fluctuations*

Hay and Pasquill [5] and Cramer [6, 7] have suggested the use of fluctuation statistics from fixed wind systems to estimate the dispersion taking place within pollutant plumes over finite release times. The equation used for calculating the variance of the bearings (azimuth) from the point of release of the particles, σ_p^2, at a particular downwind location is

$$\sigma_p^2 = \sigma_a^2(\tau, s) \tag{21.8}$$

where σ_a^2 is the variance of the azimuth angles of a wind vane over the sampling period τ calculated from average wind directions averaged over averaging periods of duration s; s equals T/β, where T is the travel time to the downwind location; T is equivalent to x/u, where x is the downwind distance from the source and u is the transport wind speed. Here β is the ratio of the time scale of the turbulence moving with the air stream (Lagrangian) to the time scale of the turbulence at a fixed point (Eulerian). Although β has considerable variation (from about 1 to 9), a reasonable fit to field data has been found using a value of 4 for β.

A similar equation can be written for vertical spread from an elevated source. The standard deviation of the vertical distribution of pollutants at the downwind distance x is given by

$$\sigma_z = \sigma_e(\tau, s)x \tag{21.9}$$

where σ_z is in meters and σ_e is the standard deviation of the elevation angle, in radians, over the sampling period τ calculated from averaged elevation angles over averaging periods s. Here, as before, s equals T/β where T is travel time, and β can be approximated as equal to 4; x in Eq. (21.9) is in meters. In application, σ values can be calculated over several set averaging periods s. The distances to which each σ applies are then given by $x = \beta us$.

To calculate plume dispersion directly from fluctuation measurements, Draxler [8] used equations in the form:

$$\sigma_y = x\sigma_a f_y \tag{21.10}$$

$$\sigma_z = x\sigma_e f_z \tag{21.11}$$

He analyzed dispersion data from 11 field experiments in order to determine the form of the functions f_y and f_z, including release height effects. Irwin [9] has used simplified expressions for these functions where both f_y and f_z have the form:

$$f = 1/[1 + 0.9(T/T_0)^{0.5}] \tag{21.12}$$

where travel time T is x/u; T_0 is 1000 for f_y; T_0 is 500 for f_z for unstable (including daytime neutral) conditions; and T_0 is 50 for f_z for stable (including nighttime neutral) conditions.

2. By Classification of Wind Direction Traces

Where specialized fluctuation data are not available, estimates of horizontal spreading can be approximated from convential wind direction traces. A method suggested by Smith [2] and Singer and Smith [10] uses classification of the wind direction trace to determine the turbulence characteristics of the atmosphere, which are then used to infer the dispersion. Five turbulence classes are determined from inspection of the analog record of wind direction over a period of 1 h. These classes are defined in Table 21.1. The atmosphere is classified as A, B_2, B_1, C, or D. At Brookhaven National Laboratory, where the system was devised, the most unstable category, A, occurs infrequently enough that insufficient information is available to estimate its dispersion parameters. For the other four classes, the equations, coefficients, and exponents for the dispersion parameters are given in Table 21.2, where the source to receptor distance x is in meters.

TABLE 21.1

Brookhaven Gustiness Classes (Based on Variations of Horizontal Wind Direction over 1 h at the Height of Release)

A	Fluctuations of wind direction exceeding 90°
B_2	Fluctuations ranging from 45° to 90°
B_1	Similar to A and B_2, with fluctuations confined to a range of 15–45°
C	Distinguished by the unbroken solid core of the trace, through which a straight line can be drawn for the entire hour without touching "open space." The fluctuations must be 15°, but no upper limit is imposed
D	The trace approximates a line. Short-term fluctuations do not exceed 15°

Source: From Singer and Smith [10].

TABLE 21.2

Coefficients and Exponents for Brookhaven Gustiness Classes

Type	a	b	c	d
B_2	0.40	0.91	0.41	0.91
B_1	0.36	0.86	0.33	0.86
C	0.32	0.78	0.22	0.78
D	0.31	0.71	0.06	0.71

Note: $\sigma_y = ax^b$; $\sigma_z = cx^d$ (x is in meters).
Source: Adapted from Table 1 of Gifford [12].

3. *By Classification of Atmospheric Stability*

Pasquill [11] advocated the use of fluctuation measurements for dispersion estimates but provided a scheme "for use in the likely absence of special measurements of wind structure, there was clearly a need for broad estimates" of dispersion "in terms of routine meteorological data". The first element is a scheme which includes the important effects of thermal stratification to yield broad categories of stability. The necessary parameters for the scheme consist of wind speed, insolation, and cloudiness, which are basically obtainable from routine observations (Table 21.3).

TABLE 21.3

Pasquill Stability Categories

	Isolation			Night	
Surface wind speed ($m\ s^{-1}$)	Strong	Moderate	Slight	Thinly overcast or ≥4/8 low cloud	≤3/8 cloud
<2	A	A–B	B	—	—
2–3	A–B	B	C	E	F
3–5	B	B–C	C	D	E
5–6	C	C–D	D	D	D
>6	C	D	D	D	D
	(for A–B, take the average of values for A and B, etc.)				

Notes:
1. Strong insolation corresponds to sunny midday in midsummer in England; slight insolation to similar conditions in midwinter.
2. Night refers to the period from 1 h before sunset to 1 h after sunrise.
3. The neutral category D should also be used, regardless of wind speed, for overcast conditions during day or night and for any sky conditions during the hour preceding or following night as defined above.
Source: From Pasquill [13].

Pasquill's dispersion parameters were restated in terms of σ_y and σ_z by Gifford [14, 15] to allow their use in the Gaussian plume equations. The parameters σ_y and σ_z are found by estimation from the graphs (Fig. 21.6), as a function of the distance between source and receptor, from the appropriate curve, one for each stability class [12]. Alternatively, σ_y and σ_z can be calculated using the equations given in Tables 21.4 and 21.5, which are used in the point source computer techniques PTDIS and PTMTP [16]. These parameter values are most applicable for releases near the ground (within about 50 m).

Other estimations of σ_y and σ_z by Briggs for two different situations, urban and rural, for each Pasquill stability class, as a function of distance between source and receptor, are given in Tables 21.6 and 21.7 [12].

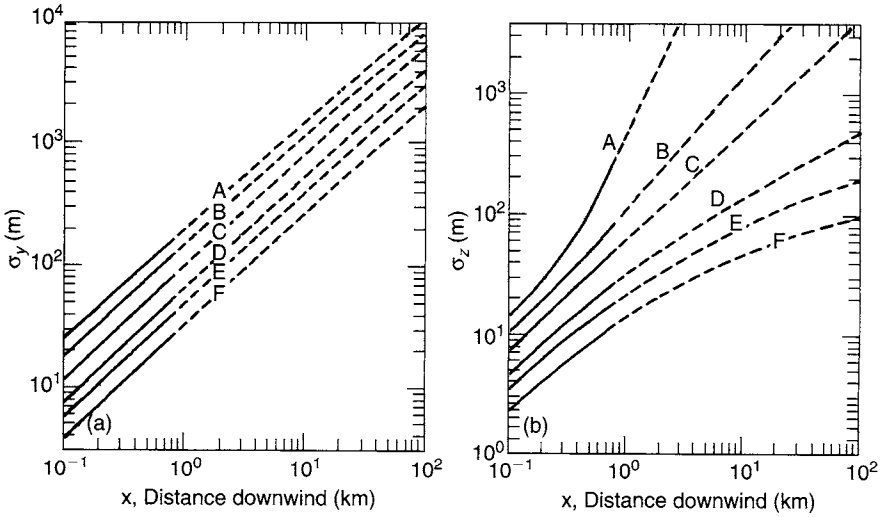


Fig. 21.6. Pasquill–Gifford: (a) σ_y and (b) σ_z. *Source*: From Gifford [12].

TABLE 21.4

Pasquill–Gifford Horizontal Dispersion Parameter

Stability	Parameter		
A	$T = 24.167$	-2.5334	$\ln x$
B	$T = 18.333$	-1.8096	$\ln x$
C	$T = 12.5$	-1.0857	$\ln x$
D	$T = 8.3333$	-0.72382	$\ln x$
E	$T = 6.25$	-0.54287	$\ln x$
F	$T = 4.1667$	-0.36191	$\ln x$

Note: σ_y (m) $= 465.116\, x \tan T$; x is downwind distance in km; T is one-half Pasquill's θ (degrees).

TABLE 21.5

Pasquill–Gifford Vertical Dispersion Parameter

Stability	Distance (km)	a	b	$\sigma_z{}^a$
A	>3.11			5000 m
	0.5–3.11	453.85	2.1166	
	0.4–0.5	346.75	1.7283	104.7
	0.3–0.4	258.89	1.4094	71.2
	0.25–0.3	217.41	1.2644	47.4
	0.2–0.25	179.52	1.1262	37.7
	0.15–0.2	170.22	1.0932	29.3
	0.1–0.15	158.08	1.0542	21.4
	<0.1	122.8	0.9447	14.0
B	>35			5000 m
	0.4–35	109.30	1.0971	
	0.2–0.4	98.483	0.98332	40.0
	<0.2	90.673	0.93198	20.2
C	all x	61.141	0.91465	
D	>30	44.053	0.51179	
	10–30	36.650	0.56589	251.2
	3–10	33.504	0.60486	134.9
	1–3	32.093	0.64403	65.1
	0.3–1	32.093	0.81066	32.1
	<0.3	34.459	0.86974	12.1
E	>40	47.618	0.29592	
	20–40	35.420	0.37615	141.9
	10–20	26.970	0.46713	109.3
	4–10	24.703	0.50527	79.1
	2–4	22.534	0.57154	49.8
	1–2	21.628	0.63077	33.5
	0.3–1	21.628	0.75660	21.6
	0.1–0.3	23.331	0.81956	8.7
	<0.1	24.260	0.83660	3.5
F	>60	34.219	0.21716	
	30–60	27.074	0.27436	83.3
	15–30	22.651	0.32681	68.8
	7–15	17.836	0.4150	54.9
	3–7	16.187	0.4649	40.0
	2–3	14.823	0.54503	27.0
	1–2	13.953	0.63227	21.6
	0.7–1.0	13.953	0.68465	14.0
	0.2–0.7	14.457	0.78407	10.9
	<0.2	15.209	0.81558	4.1

[a] σ_z at boundary of distance range for all values except 5000 m.
Note: σ_z (m) = ax^b; x is downwind distance in km.

D. Example of a Dispersion Calculation

As an example of the use of the Gaussian plume equations using the Pasquill–Gifford dispersion parameters, assume that a source releases 0.37 g s^{-1} of a pollutant at an effective height of 40 m into the atmosphere with the wind blowing at 2 m s^{-1}. What is the approximate distance of the

TABLE 21.6

Urban Dispersion Parameters by Briggs (for Distances Between 100 and 10 000 m)

Pasquill type	σ_y, m	σ_z, m
A–B	$0.32x(1 + 0.0004x)^{-0.5}$	$0.24x(1 + 0.001x)^{0.5}$
C	$0.22x(1 + 0.0004x)^{-0.5}$	$0.20x$
D	$0.16x(1 + 0.0004x)^{-0.5}$	$0.14x(1 + 0.0003x)^{-0.5}$
E–F	$0.11x(1 + 0.0004x)^{-0.5}$	$0.08x(1 + 0.0015x)^{-0.5}$

Source: From Gifford [12].

TABLE 21.7

Rural Dispersion Parameters by Briggs (for Distances Between 100 and 10 000 m)

Pasquill type	σ_y, m	σ_z, m
A	$0.22x(1 + 0.0001x)^{-0.5}$	$0.20x$
B	$0.16x(1 + 0.0001x)^{-0.5}$	$0.12x$
C	$0.11x(1 + 0.0001x)^{-0.5}$	$0.08x(1 + 0.0002x)^{-0.5}$
D	$0.08x(1 + 0.0001x)^{-0.5}$	$0.06x(1 + 0.0015x)^{-0.5}$
E	$0.06x(1 + 0.0001x)^{-0.5}$	$0.03x(1 + 0.0003x)^{-1}$
F	$0.04x(1 + 0.0001x)^{-0.5}$	$0.016x(1 + 0.0003x)^{-1}$

Source: From Gifford [12].

maximum concentration, and what is the concentration at this point if the atmosphere is appropriately represented by Pasquill stability class B?

Solution: The maximum occurs approximately when $\sigma_z = H/(2)^{1/2} = 28.3$ m. Under B stability, this occurs at $x = 0.28$ km. At this point $\sigma_y = 49.0$ m (from Table 21. 4). First, the maximum can be estimated by Eq. (21.5):

$$\chi_{\max} = \frac{2Q}{\pi ueH^2}\frac{\sigma_z}{\sigma_y} = \frac{2(0.37)}{\pi 2e40^2}\frac{28.3}{49.0} = 1.56 \times 10^{-5}\,\text{g m}^{-3}$$

To see if this is approximately the distance of the maximum, the equation

$$\chi = [Q/(\pi u\sigma_y\sigma_z)]\exp[-0.5(H/\sigma_z)^2] \tag{21.13}$$

which results from Eq. (21.2) with y and z equal to 0, is evaluated at three distances: 0.26, 0.28, and 0.30 km. The parameter values and the resulting concentrations are given in the following table:

x, km	σ_z, m	σ_y, m	χ, g m^{-3}
0.26	26.2	45.9	1.53×10^{-5}
0.28	28.2	49.0	1.56×10^{-5}
0.30	30.1	52.2	1.55×10^{-5}

σ_z is obtained from equations in Table 21.5.
σ_y is obtained from equations in Table 21.4.

which verifies that, to the nearest 20 m, the maximum is at 0.28 km. Note that the concentration obtained from this equation is the same as that obtained from the approximation equation for the maximum.

Buoyancy-induced dispersion, which is caused near the source due to the rapid expansion of the plume during the rapid rise of the thermally buoyant plume after its release from the point of discharge, should also be included for buoyant releases [15]. The effective vertical dispersion σ_{ze} is found from:

$$\sigma_{ze}^2 = (\Delta H/3.5)^2 + \sigma_z^2 \tag{21.14}$$

where ΔH, the plume rise, and σ_z are evaluated at the distance x from the source. Beyond the distance to the final rise, ΔH is a constant. At shorter distances, it is evaluated for the gradually rising plume (see Chapter 22).

Since in the initial growth phases of a buoyant plume the plume is nearly symmetrical about its centerline, the buoyancy-induced dispersion in the crosswind (horizontal) direction is assumed to be equal to that in the vertical. Thus, the effective horizontal dispersion σ_{ye} is found from

$$\sigma_{ye}^2 = (\Delta H/3.5)^2 + \sigma_y^2 \tag{21.15}$$

The Gaussian plume equations are then used by substituting the value of σ_{ye} for σ_y and σ_{ze} for σ_z.

IV. DISPERSION INSTRUMENTATION

A. Measurements near the Surface

Near-surface (within 10 m of the ground) meteorological instrumentation always includes wind measurements and should include turbulence measurements as well. Such measurements can be made at 10 m above ground by using a guyed tower. A cup anemometer and wind vane (Fig. 21. 7), or a vane with a propeller speed sensor mounted in front (Fig. 21.8), can be the basic wind system. The wind sensor should have a threshold starting speed of less than 0.5 m s^{-1}, an accuracy of 0.2 m s^{-1} or 5%, and a distance constant of less than 5 m for proper response. The primary quantity needed is the hourly average wind speed. A representative value may be obtained from values taken each minute, although values taken at intervals of 1–5 s are better.

The vane can be used for both average wind direction and the fluctuation statistic σ_a, both determined over hourly intervals. The vane should have a distance constant of less than 5 m and a damping ratio greater than or equal to 0.4 to have a proper response. Relative accuracy should be 1° and absolute accuracy should be 5°. In order to estimate σ_a accurately, the direction should be sampled at intervals of 1–5 s. This can best be accomplished by microcircuitry (minicomputer) designed to sample properly the output from the vane and perform the calculations for both mean wind and σ_a, taking into account crossover shifts of the wind past the 360° and 0° point.

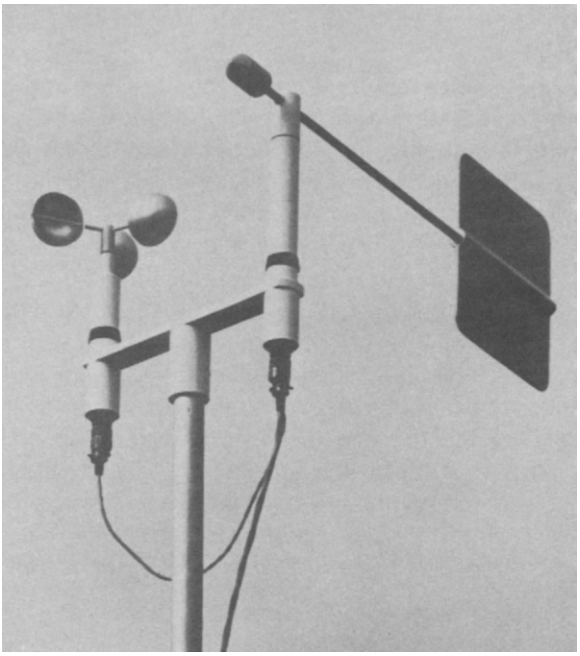


Fig. 21.7. Microvane and three-cup anemometer. *Source*: Photo courtesy of R. M. Young Co.

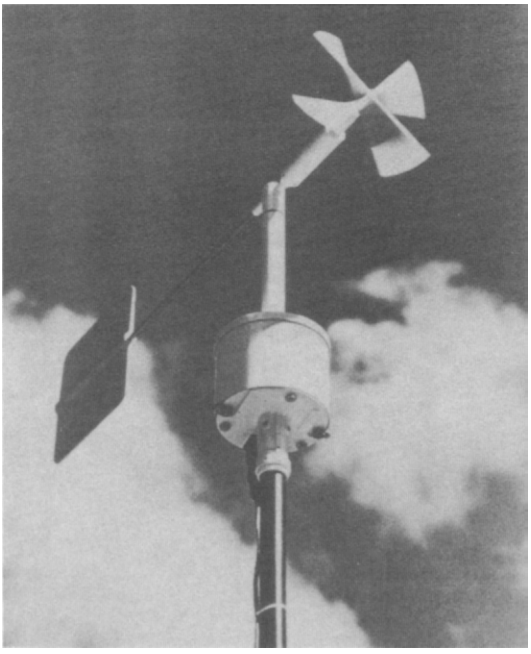


Fig. 21.8. Propeller vane wind system. *Source*: Photo courtesy of R. M. Young Co.

The elevation angle, and through appropriate data processing σ_e, can be measured with a bivane (a vane pivoted so as to move in the vertical as well as the horizontal). Bivanes require frequent maintenance and calibration and are affected by precipitation and formation of dew. A bivane is therefore more a research instrument than an operational one. Vertical fluctuations may be measured by sensing vertical velocity w and calculating σ_w from the output of a propeller anemometer mounted on a vertical shaft. The instrument should be placed away from other instrumentation and the propeller axis carefully aligned to be vertical. The specifications of this sensor are the same as those of the wind sensor. Because this instrument will frequently be operating near its lower threshold and because the elevation angle of the wind vector is small, such that the propeller will be operating at yaw angles where it has least accuracy, this method of measuring vertical velocity is not likely to be as accurate as the measurement of horizontal fluctuation.

Rather than using separate systems for horizontal and vertical wind measurements, a u–v–w anemometer system (Fig. 21.9) sensing wind along three orthogonal axes, with proper processing to give average wind direction and σ_a from the combination of the u and v components and w and σ_w from the w component may be used.

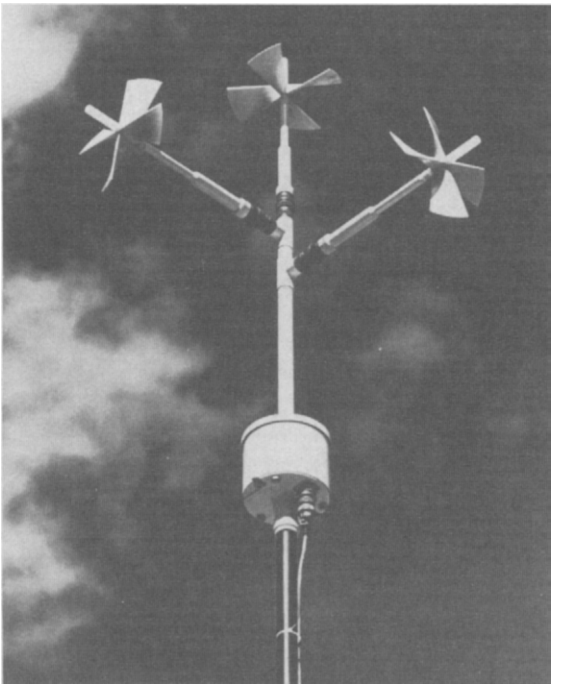


Fig. 21.9. *U, V, W* wind system. *Source*: Photo courtesy of R. M. Young Co.

Additional near-surface measurements may also be required to support calculated quantities such as the bulk Richardson number (a stability parameter):

$$\mathrm{Ri_B} = \frac{gh}{T}\frac{\theta_h - \theta_z}{u_h^2}$$

which requires a temperature gradient, a temperature, and wind speed at the height of the boundary layer h. For this purpose, in addition to the wind speed at 10 m from the instrumentation, a vertical temperature difference measurement is needed. This can be obtained for the interval of 2–10 m aboveground using two relatively slow response sensors wired to give the temperature difference directly. Again, hourly averages are of greatest interest. The specifications are response time of 1 min, accuracy of 0.1°C, and resolution of 0.02°C. Both sensors should use good-quality aspirated radiation shields to give representative values. Sensor sampling about every 30 s yields good hourly averages.

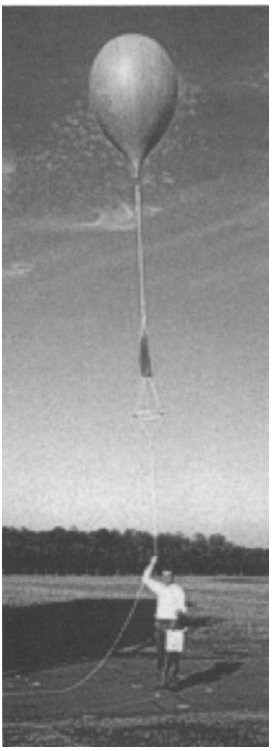
Radiation instruments are useful in determining stability such as F. B. Smith's [17] stability parameter P. Although somewhat similar to the Pasquill stability class (Table 21.3), P is continuous (rather than a discrete class) and is derived from wind speed and measurement of upward heat flux or, lacking this, incoming solar radiation (in daytime) and cloud amount at night. Pyranometers measure total sun and sky radiation. Net radiometers measure both incoming (mostly shortwave) radiation and outgoing (mostly longwave) radiation. Data from both are useful in turbulence characterization, and the values should be integrated over hourly periods. Care should be taken to avoid shadows on the sensors. The net radiometer is very sensitive to the condition of the ground surface over which it is exposed.

B. Measurements above the Surface

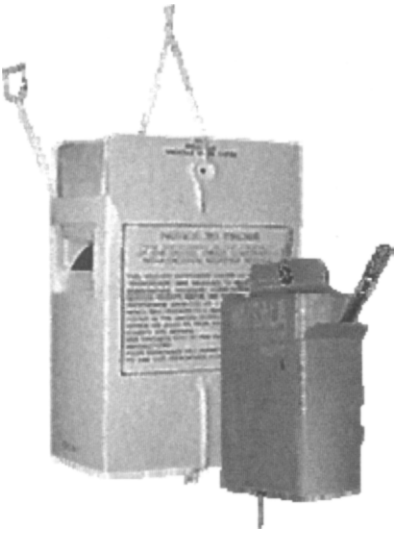
Measurements above the surface are also important to support pollutant impact evaluation. The radiosonde program of the National Weather Service (Fig. 21.10), established to support forecast and aviation weather activities, is a useful source of temperatures and data on winds aloft, although it has the disadvantage that measurements are made at 12-h intervals and the surface layer is inadequately sampled because of the fast rate of rise of the balloon. Mixing height, the height aboveground of the neutral or unstable layer, is calculated from the radiosonde information (see Chapter 5, Section II).

Measurements of wind, turbulence, and temperature aloft may also be made at various heights on meteorological towers taller than 10 m. Where possible, the sensors should be exposed on a boom at a distance from the tower equal to two times the diameter of the tower at that height.

Aircraft can take vertical temperature soundings and can measure air pollutant and tracer concentrations and turbulence intensity. Airborne lidar can



(a)



(b)

Fig. 21.10. (a) Radiosonde launch and (b) sensor transmitter. *Source:* Photos courtesy of National Oceanic and Atmospheric Administration.

measure plume heights, and integrating nephelometers can determine particle size distributions.

Since operating aircraft, building towers, and establishing instruments on towers are extremely expensive, considerable attention has focused on indirect upper-air sounding from the ground. Mixing height within the range of measurement (approximately 500–600 m aboveground) can be determined by either the Doppler or the monostatic version of sodar (sound direction and ranging) with a spatial resolution of about 30 m. Data on wind and turbulence can be determined by Doppler sodar, FM-CW radar, and lidar. Doppler sodar measurements of wind components are within approximately $0.5\,\mathrm{m\,s^{-1}}$ of tower measurements. Measurements represent 30-m volume averages in the vertical. A height of 500 m aboveground, and sometimes over 1000 m, can be reached routinely.

Some measurements that are completely impractical for routine measurement programs are useful during periods of intensive field programs. Winds and temperatures can be measured through frequent releases of balloon-carried sensors. Lidar is useful for determining plume dimensions. The particle lidar measures backscatter of laser radiation from particles in the plume

and particles in the free air. The differential absorption lidar uses two wavelengths, one with strong absorption by sulfur dioxide and the other for weak absorption. The difference determines the amount of sulfur dioxide in the plume. Positioning of the lidar and its scanning mode determines whether vertical or horizontal dimensions of the plume are measured.

C. Data Reduction and Quality Assurance

A meteorological measurement program includes data reduction, calculation of quantities not directly measured, data logging, and archiving. Special-purpose minicomputers are used for sampling sensor output at frequent intervals (down to fractions of a second), calculating averages, and determining standard deviations. The output from the minicomputer should go to a data logger so that the appropriate information can be recorded on magnetic tape or disk or paper tape. If only hourly values must be archived, a considerable period of record for all data from a site can be contained on a single tape, disk, or cassette. Hard copy from a printer is usually also obtained. Immediate availability of this copy can aid in detecting system or sensor malfunctions. Sometimes analog charts are maintained for each sensor to provide backup data recovery (in case of reduction error or data logger malfunction) and to detect sensor malfunction.

An extremely important part of a measurement program is an adequate quality assurance program. Cost cutting in this part of the program can result in useless measurements. A good-quality assurance program includes calibration of individual components and of the entire system in the laboratory; calibration of the system upon installation in the field; scheduled maintenance and servicing; recalibration (perhaps quarterly); and daily examination of data output for unusual or unlikely values. More frequent servicing than that recommended by manufacturers may be required when sensors are placed in polluted atmospheres which may cause relatively rapid corrosion of instrument parts.

V. ATMOSPHERIC TRACERS

A. Technique

Tracer studies are extremely important in furthering our knowledge of atmospheric dispersion. These studies consist of release of a known quantity of a unique substance (the tracer), with measurements of that substance at one or more downwind sampling locations. Early experiments released uranine dye as a liquid spray; the water evaporated, leaving fine fluorescent particles to be sampled. Later, dry fluorescent particles (e.g. zinc–cadmium sulfide) having a relatively narrow range of particle sizes were used. Since the early 1970s, the gas sulfur hexafluoride has been used for most tracer

studies, with collection in bags at sampling locations for later laboratory analysis using electron-capture gas chromatography.

Most recently, the US Departments of Homeland Security, Energy, and Commerce, and the Environmental Protection Agency (EPA) have used perfluoride tracers (PFTs) in their Urban Dispersion Program. The PFTs have the advantage over sulfur hexafluoride in that there are a very few sources that may interfere with the measurements. In addition, the various chemical forms of PFTs can be readily identified at very low concentrations (circa parts per quadrillion). Having a number of different chemical forms allows the tracer measurements to be linked to different sources. In fact, this was accomplished in tracer studies conducted in New York City in 2005 (see Fig. 21.11 and Fig. 21.12) [22].

Tracer studies are generally conducted by going into the field for a 2-week to 1-month intensive study period. The tracer is released, generally from a constant height, continuously at a constant rate for a set period (perhaps 2–3 h) on a day selected for its meteorological conditions with the wind forecast to blow toward the sampling network. Sampling equipment is arranged at ground level on constant-distance arcs usually at three or four distances. The samplers begin at a set time as switched on by the field crew or by radio control. More sophisticated samplers allow the unattended collection sequentially of several samples. Sampling time varies from around 20 min to several hours. This procedure measures horizontal dispersion at the height of the samplers.

Although it is highly desirable to determine vertical dispersion as well by direct measurement, it is seldom practical. Sampling in the vertical can be done by sampling on fixed towers or arranging samplers along the cables of captive balloons. Both of these methods are extremely expensive in terms of both equipment and personnel. Although it is possible to sample the tracer with aircraft, the pass through the pollutant plume occurs at such high speed that it is difficult to relate this instantaneous sample to what would occur over a longer sampling time of from 20 min to 1 h.

B. Computations

If the tracer concentration is χ_i measured at each sampling position that has its position at y_i on a scale along the arc (either in degrees or in meters), estimates of the mean position of the plume at ground level and the variance of the ground-level concentration distribution are given by:

$$y = \frac{\Sigma \chi_i y_i}{\Sigma \chi_i} \tag{21.16}$$

$$\sigma_y^2 = \frac{\Sigma \chi_i \, \Sigma \chi_i y_i^2 - (\Sigma \chi_i y_i)^2}{(\Sigma \chi_i)^2} \tag{21.17}$$

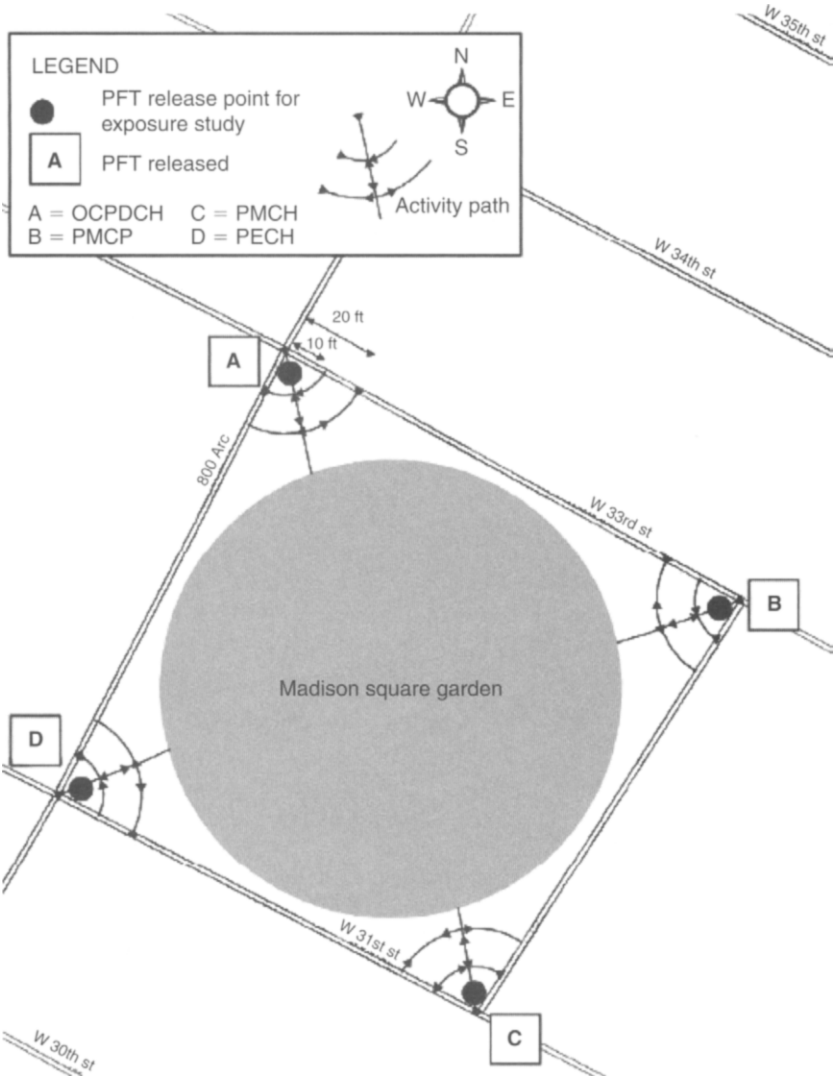


Fig. 21.11. Location of perfluoride tracer (PFT) releases in March 2005 Urban Dispersion Program study around Madison Square Garden in New York City. The tracers are: PMCP (perfluoromethylcyclopentane), oc-PDCH (perfluoro-1,2-dimethylcyclohexane), PMCH (perfluoromethylcyclohexane), and PECH (perfluoroethylcyclohexane). *Source*: Lioy, P., Vallero, D., Foley, G., Georgopoulos, P., Heiser, J., Watson, T., Reynolds, M., Daloia, J., Tong, S., and Isukapal, S., A personal exposure study employing scripted activities and paths in conjunction with atmospheric releases of perfluorocarbon tracers in Manhattan, New York. *J. Exposure Sci. Environ. Epidemiol.*, 17, 409–425 (2007).

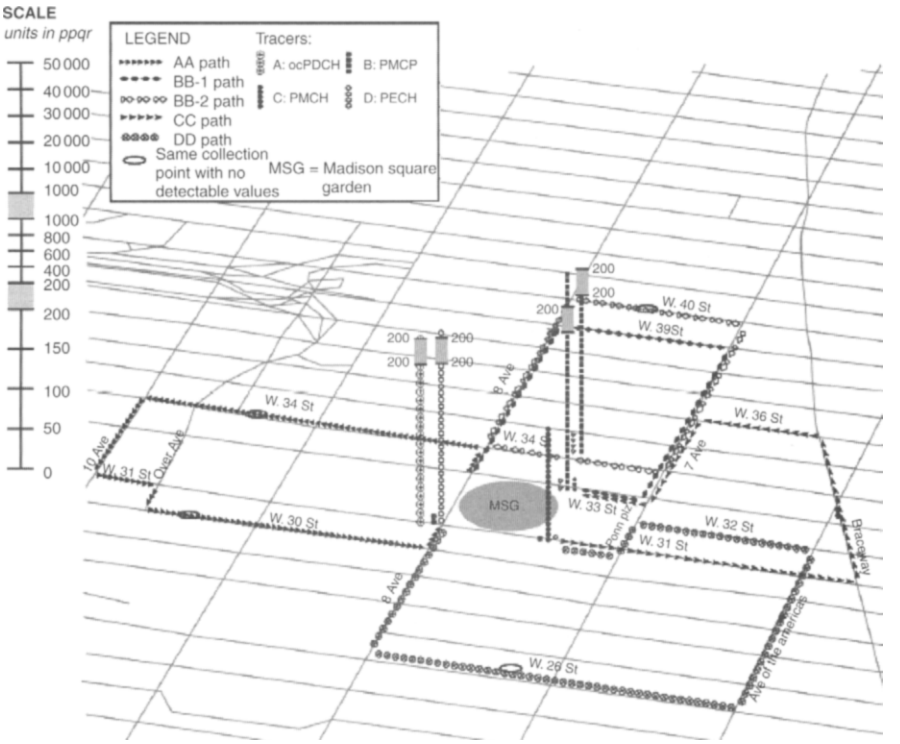


Fig. 21.12. Neighborhood scale personal exposure monitoring, 9:00–9:30 a.m., during release of PFTs on March 10, 2005 releases in the Urban Dispersion Program study around Madison Square Garden in New York City. The tracers are: PMCP (perfluoromethylcyclopentane), oc-PDCH (perfluoro-1,2-dimethylcyclohexane), PMCH (perfluoromethylcyclohexane), and PECH (perfluoroethylcyclohexane). *Source*: Lioy, P., Vallero, D., Foley, G., Georgopoulos, P., Heiser, J., Watson, T., Reynolds, M., Daloia, J., Tong, S., and Isukapal, S. A personal exposure study employing scripted activities and paths in conjunction with atmospheric releases of perfluorocarbon tracers in Manhattan, New York.*J. Exposure Sci. Environ. Epidemiol.*, 17, 409–425 (2007).

In the example shown in Fig. 21.13, measurements were made every 2° on an arc 5 km from the source. The mean position of the plume is at an azimuth of 97.65° and the standard deviation is 4.806°.

$$\sigma_y(\text{meters}) = \sigma_y(\text{degrees})\frac{\pi}{180}x\ (\text{meters}) \tag{21.18}$$

In this case σ_y is 419 m. The peak concentration can be found from the measurements, or from the Gaussian distribution fitted to the data and the peak concentration obtained from the fitted distribution. Provided that the emission rate Q, the height of release H, and the mean wind speed u are known, the standard deviation of the vertical distribution of the pollutant

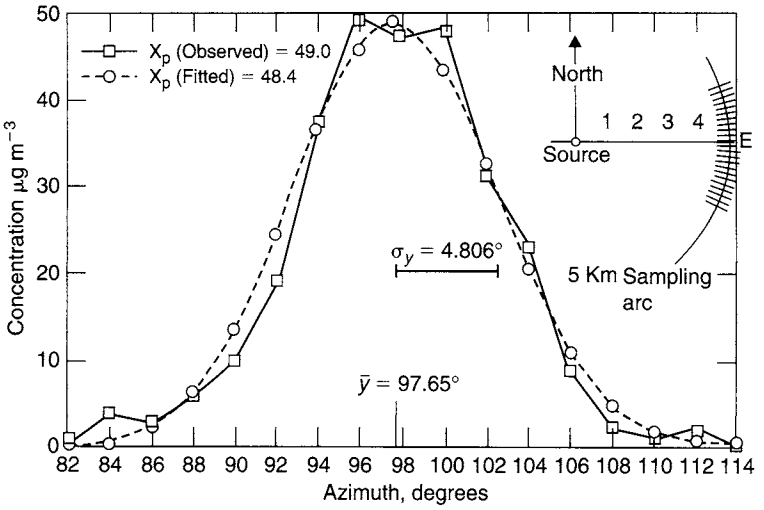


Fig. 21.13. Example of tracer concentration measurements along a sampling arc.

can be approximated from either the peak concentration (actual or fitted) or the crosswind integrated (CWI) concentration from one of the following equations:

$$\sigma_z \exp 0.5(H/\sigma_z)^2 = 2Q/[(2\pi)^{0.5}\, u\chi_{\mathrm{CWI}}] \tag{21.19}$$

$$\sigma_z \exp 0.5(H/\sigma_z)^2 = Q/[(\pi)u\sigma_y\, \chi_{\mathrm{peak}}] \tag{21.20}$$

The CWI concentration in g m^{-2} may be approximated from the tracer measurements from

$$\chi_{\mathrm{CWI}} = \text{sampler spacing (meters)}\ \Sigma\chi_i \tag{21.21}$$

Using the data from Fig. 21.14, the calculated σ_z from the CWI concentration is 239 m; from the observed peak concentration it is 232 m; and from the fitted peak concentration it is 235 m. Note that errors in any of the parameters H, Q, or u, will cause errors in the estimated σ_z.

Although extremely useful, tracer experiments require considerable capital expenditures and personnel. In addition to the difficulties and uncertainty in making estimates of various parameters, especially σ_z, one of the difficulties in interpreting tracer studies is relating the atmospheric conditions under which the study was conducted to the entire spectrum of atmospheric conditions. For example, trying to interpret a series of tracer experiments, even if conducted over a relatively large number of hours, in relation to the conditions that cause the second highest concentration once a year is extremely difficult, if not impossible.

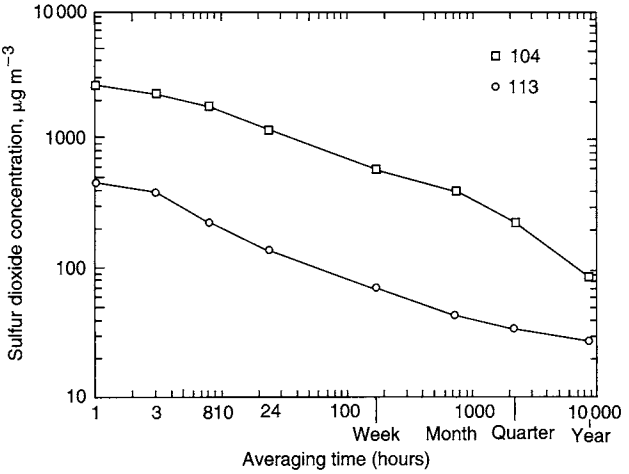


Fig. 21.14. Variation of St. Louis SO_2 maximum concentrations with sampling time for locations with highest (station 104) and lowest (station 113) maximum 1-h concentrations.

VI. CONCENTRATION VARIATION WITH AVERAGING TIME

If emission and meteorological conditions remained unchanged hour after hour, concentrations at various locations downwind would remain the same. However, since such conditions are ever-changing, concentrations vary with time. Even under fairly steady meteorological conditions, with the mean wind direction remaining nearly the same over a period of some hours, as the averaging time increases, greater departures in wind direction from the mean are experienced, thus spreading the time-averaging plume more and reducing the longer averaging time concentration compared with that experienced for shorter averaging times at the location of the highest concentrations. This effect is more pronounced for receptors influenced by single point sources than for those influenced by a number of point sources or by a combination of point and area sources, because there will be many hours when the wind is not blowing from the source to the receptor.

Figure 21.12 shows the maximum sulfur dioxide concentrations for eight averaging times over a 1-year period (1976) for two air monitoring stations in the Regional Air Monitoring (RAM) network in St. Louis. These two monitoring stations, 104 and 113, have the highest and lowest maximum 1-h concentrations of the 13 stations with sulfur dioxide measurements. These maximum concentrations deviate only slightly from a power law relation:

$$\chi_p = a t_p^b \tag{21.22}$$

where χ_p is the maximum concentration for the period p, t_p is the averaging time in hours, and a and b are appropriate constants. The power b is -0.28 for station 104 and -0.33 for station 113.

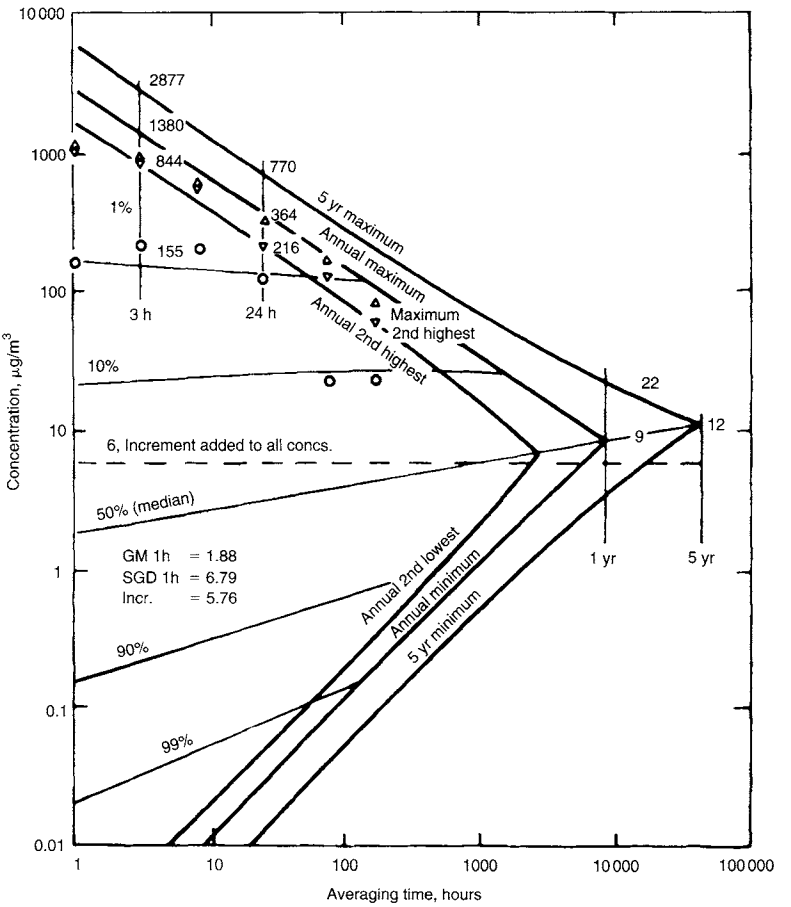


Fig. 21.15. Three-parameter averaging-time model fitted through the arithmetic mean and the second highest 3-h and 24-h SO_2 concentrations measured in 1972 a few miles from a coal-burning power plant. *Source*: From Larsen [21].

Larsen [18–21] has developed averaging time models for use in analysis and interpretation of air quality data. For urban areas where concentrations for a given averaging time tend to be lognormally distributed, that is, where a plot of the log of concentration versus the cumulative frequency of occurrence on a normal frequency distribution scale is nearly linear, the two-parameter averaging time model (Fig. 8.6) is adequate. The two parameters are the geometric mean and the standard geometric deviation. If these two parameters for a pollutant at a site can be determined for an averaging time, the model can calculate them and the annual maximum concentration expected for any other averaging time. For receptors in the vicinity of point sources, where for a given averaging time many concentrations will be zero, a three-parameter averaging time model is required. The third parameter is an increment (positive or negative) that is added to every observed concentration. In Fig. 21.15, showing

the three-parameter model applied to data from the vicinity of a power plant, 6 μg m^{-3} have been added to each observed concentration.

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QUESTIONS

1. In a situation under stable conditions with a wind speed of 4 m s^{-1} and $\sigma_a = 0.12$ radians, the wind is blowing directly toward a receptor 1 km from the source. How much must the wind

shift, in degrees, to reduce the concentration to 10% of its previous value? (At 2.15σ from the peak, the Gaussian distribution is 0.1 of the value at the peak.)

2. If the variation in wind speed with height is well approximated with a power law wind profile having an exponent equal to 0.15, how much stronger is the wind at 100 m above ground than at 10 m?
3. At a particular downwind distance, a dispersing plume is approximately 40 m wide. Which of the following three turbulent eddy diameters—5 m, 30 m, or 100 m—do you believe would be more effective in further dispersing this plume?
4. A pollutant is released from an effective height of 50 m and has a ground-level concentration of 300 $\mu g\ m^{-3}$ at a position directly downwind where the σ_z is 65 m. How does the concentration at 50 m above this point, that is, the plume centerline, compare with this ground-level concentration?
5. At a downwind distance of 800 m from a 75-m source having an 180-m plume rise, σ_y is estimated as 84 m and σ_z is estimated as 50 m. If one considers buoyancy-induced dispersion as suggested by Pasquill, by how much is the plume centerline concentration reduced at this distance?
6. Consider the parameters that need to be measured and the instrumentation needed to make the measurements for monitoring dispersion of effluent from a 30-m stack.
7. A tracer experiment includes sampling on an arc at 1000 m from the source. If the horizontal spread is expected to result in a σ_y between 120 and 150 m at this distance, and if the wind direction is within $\pm 15°$ azimuth of that forecast, how many samplers should be deployed and what should be that spacing? It is desirable to have above seven measurements within $\pm 2\sigma_y$ of the plume centerline and at least one sample on each side of the plume.
8. For a tracer release that can be considered to be at ground level, approximate the vertical dispersion σ_z at the downwind distance where measurements indicate that the concentration peak is $7 \times 10^{-8}\ g\ m^{-3}$, the horizontal σ_y is 190 m, and the crosswind integrated concentration is $3.16 \times 10^{-5}\ g\ m^{-3}$. The tracer release rate is 0.01 $g\ s^{-1}$ and the wind speed is 3.7 $m\ s^{-1}$.
9. The maximum 1-h concentration at an urban monitoring station is 800 $\mu g\ m^{-3}$. If the concentration varies with averaging time with a power law relation when the power is –0.3, what is the expected maximum concentration for a 1-week averaging time?