Integration of Roughness into Dispersion Models

4.1. Objectives and Fundamental Physical Concepts

The objective of this chapter is to describe how structures or obstacles (such as buildings and storage tanks) at an industrial site or an urban site affect transport and dispersion and show how these effects can be parametrized in consequence models, using the principles presented in Chapters 1 through 3.

It is generally true that the maximum normalized near-ground-level concentration, $C/Q$, on the centerline of the pollutant cloud depends on the speed (called the effective transport or advective speed $u_e$) at which the cloud is moving, and on the turbulent dispersion coefficients, $\sigma_x$, $\sigma_y$, and $\sigma_z$. Of course, this statement is true for clouds released below or above the average roughness obstacle height, $H_r$. It has been shown in Chapters 2 and 3 that the effective advective speed, $u_e$, and the turbulent dispersion coefficients, $\sigma_x$, $\sigma_y$, and $\sigma_z$, are all proportional to the friction velocity, $u^*$, and $u^*$ itself will, in general, increase as the surface roughness increases.

Figure 15 provides a schematic view of the various regimes discussed in previous chapters and emphasized in this chapter. In both parts of the figure, a similar urban/industrial grouping of surface
roughness obstacles is shown with average obstacle height $H_r$. The top part of the figure illustrates the vertical cloud growth for a near-ground release, where the cloud is initially confined below $H_r$, then passes through a transition regime with the cloud depth approximately equal to $H_r$, and finally reaches a regime where the bulk of the mass of the cloud is above $H_r$. These three regimes are discussed in more detail in later sections. The bottom part of the figure illustrates the vertical cloud growth for a release well above $H_r$, where the bulk of the mass of the cloud remains above $H_r$ even after the cloud base has dispersed down to the ground. Note that the range of heights defined by $0.5 H_r$ to $2 H_r$ is commonly called the urban roughness sublayer.

Figure 16 is included in order to show how the cloud advective speed, $u_c$, will increase as the cloud grows vertically as it moves down-
wind, for clouds released near the ground. The corresponding boundary-layer wind profile is drawn on the left side of the figure. Each $u_e$ vector is drawn at the mass-weighted mean height of the cloud, which is defined in Eq. (1) and which is generally assumed to equal about 0.5 to 1.0 $\sigma_z$ for a cloud on the ground.

Section 2.3.2 illustrated the dependence of plume centerline normalized concentration, $C/Q$, on $z_0$ and on $u^*$ for a simple Gaussian plume model. To illustrate the importance of $u^*$, consider the simple Monin–Obukhov similarity model for near-ground-level releases. Assume a straightforward scenario where a continuous plume is released at rate $Q$ from the ground during nearly neutral conditions over a uniform surface such that the cloud depth exceeds $H_r$. In this case, the friction velocity $u^*$, and the downwind distance, $x$, are found to completely determine the solution for the plume centerline normalized concentration, $C/Q$, and for the crosswind-integrated normalized concentration, $C_y/Q$ (Hanna et al. 1990, Britter et al. 2000). $C_y$ is defined as $\int C \, dy$, where the integration takes place along a horizontal line perpendicular to the plume centerline axis. The following equations express these simple relationships and have been validated by Hanna et al. (1990) using data from the Prairie Grass dispersion experiment.

$$\frac{C}{Q} = \frac{3.0}{(u^* x^2)} \quad (46)$$

$$\frac{C_y}{Q} = \frac{1.6}{(u^* x)} \quad (47)$$

The Prairie Grass experiments involved neutrally buoyant plumes (i.e., passive dispersion). Equations (46) and (47) have been shown to
be valid for nearly neutral conditions (i.e., very large $L$) over distances, $x$, ranging from 50 to 800 m at the Prairie Grass site. For nonneutral ambient boundary layers, a simple power law function of $x/L$ is added to the equations. These equations show that $C/Q$ and $C_v/Q$ are inversely proportional to the friction velocity, $u^*$, thus implying that $C/Q$ and $C_v/Q$ will decrease as roughness increases, since $u^*$ is increased by an increase in roughness.

For negatively buoyant (i.e., dense gas) releases at ground level, Briggs et al. (2001) studied three parallel experiments in different wind tunnels and found (somewhat surprisingly) that all the effects of surface roughness on vertical dispersion were through the variation of $u^*$ with $z_0$. The form of their equation is similar to Eq. (47), with a correction for plume density. These experiments involved cloud depths evolving from less than $H_r$ through much greater than $H_r$, similar to the scenario depicted in the top part of Figure 15.

If a cloud is released at a height much greater than $H_r$, as shown in the bottom part of Figure 15, the ground-level concentration can be estimated by the simple Gaussian plume model [Eq. (9)], with $u_e$ constant (at the height of release). As before, $u_e$ and the turbulent dispersion coefficients are all proportional to $u^*$. For such releases, the near-field maximum concentrations at ground level are likely to increase as the roughness increases due to the enhanced vertical dispersion, which more quickly disperses the base of the plume to the ground. It is also possible in many situations for concentrations at ground level to increase near roughness obstacles such as buildings and storage tanks if the elevated plume is caught in the wake behind individual obstacles and mixed down to the ground. At larger distances downwind, as seen on the right side of the bottom part of Figure 15, the cloud is well-mixed all the way down to the ground surface (i.e., $\sigma_z$ exceeds the source release height), and the effect of increases in surface roughness will be to decrease the ground-level concentrations, in the same way as for near-surface releases.

If a cloud is released at a height much lower than $H_r$ and the cloud depth is smaller than $H_r$, as shown on the left side of the top part of Figure 15, the concentration prediction equations are slightly different from Eqs. (46) and (47) but the wind speed and the dispersion coefficients are still proportional to $u^*$. In most of these cases where the cloud is below $H_r$, concentrations will decrease as the roughness increases. However, in some situations involving ground-level releases of contin-
uous plumes or clouds in more densely packed obstacle arrays, when the cloud height is lower than $H_r$, ground-level concentrations may not decrease as roughness obstacle heights increase. Because the wind speed acts to dilute a continuous plume or cloud, if the wind speed is markedly decreased down within the obstacles, the reduction in dilution may sometimes dominate over the increase in turbulent velocities and may cause $C/Q$ to increase. This situation is most likely to happen for dense obstacle packing (i.e., large $\lambda_f$ and $\lambda_p$).

It is important to have the solutions exhibit a smooth transition in the urban roughness sublayer between the “above $H_r$” case and the “below $H_r$” case (i.e., for the two cases shown in Figure 15). Also, the transition should be smooth for the “below $H_r$” case as the cloud is carried downwind and passes through the three regimes shown in the top part of Figure 15. Otherwise there could be large differences in model calculations of $C/Q$ over very short increments of distances. It will be seen that, since our methodology depends so strongly on $u^*$, the transition is smooth.

The Gaussian model [e.g., Eq. (9)] is used as the basis for our discussions in subsequent sections. It is assumed that the Gaussian model applies both above and below $H_r$, and that all we have to do is specify the cloud speed $u$ (or more accurately, $u_c$) and the three dispersion coefficients ($\sigma_x$, $\sigma_y$ and $\sigma_z$), which are all functions of $u^*$ and therefore are functions of $z_o$ and $d$.

The following sections describe the recommended approaches. They are divided into categories according to whether the cloud extends above $H_r$, is below $H_r$, or is approximately equal to $H_r$.

4.2. Dispersion Models for Clouds Extending Above $H_r$

4.2.1. Introduction to General Characteristics of Models

If the cloud depth and/or the cloud release height greatly exceed $H_r$, the problem simplifies to the standard atmospheric transport and dispersion problem studied by researchers and model developers for decades. This is the situation depicted on the right side of the top panel and depicted in the entire bottom panel of Figure 15. Dozens of models exist and are used for a wide variety of purposes, including regulatory applications and hazard assessments (e.g., DeVauill et al., 1995; Hanna et al., 1996).
Whether the model is a Gaussian plume or puff model, a similarity model [see Eqs. (46) and (47)], a Lagrangian particle dispersion model, an Eulerian grid model, or any other model dependent on knowledge of the atmospheric boundary layer, Monin–Obukhov scaling applies and the model parameters can be expressed in terms of $u^*$ and $L$, or $w^*$ and $z_i$ in convective conditions. All models require an estimate of the cloud advection speed, $u_c$, and a measure of the rate of dispersion. Therefore, the concepts discussed in this book are applicable to any of these types of models. As was well established in Chapters 1 through 3, estimation of $z_o$ and $d$ are crucial to estimation of $u^*$.

If the cloud is denser than air or is more buoyant than air, the transport and dispersion will also depend on the difference between the cloud density and the air density. For example, a dense cloud will tend to have a smaller vertical size and a larger lateral size than a neutrally buoyant cloud. A positively buoyant cloud, such as a hot plume from a combustion process, may be dominated by its internal buoyancy rather than ambient turbulence in its initial stages and may rise above the height at which it was initially released.

4.2.2. Summary of Dispersion Experiments over Rough Surfaces

As discussed in Section 2.4, full-scale urban tracer experiments, such as the St. Louis tracer study (McElroy and Pooler, 1968), confirm our expectations that, for a given stability class, the dispersion coefficients for urban conditions are consistently larger than the dispersion coefficients for rural conditions. On a smaller scale, but still in the field, the Kit Fox field experiments demonstrate a very clear trend, where the maximum normalized concentration, $C/Q$, on the plume centerline decreases as the surface roughness increases. The observed maximum $C/Q$ values at the Kit Fox site are proportional to $z_o^{-1/2}$; i.e., the maximum $C/Q$ decreases by about a factor of about three with each order of magnitude increase in $z_o$.

Some laboratory studies have been made of flow and dispersion over arrays of roughness elements where the plume size exceeds $H$, and therefore the elements can be parametrized through $z_o$. These studies confirm that the concentration would decrease as the roughness increases, for all other conditions the same (see Roberts et al., 1994). Other laboratory data confirm that it is appropriate to parametrize the effects of an industrial area on dispersion by means of a surface roughness length, $z_o$ (see Britter et al., 1991)
Most of the small-scale field studies and laboratory studies have made use of obstacles with uniform shapes and sizes. Consequently, these results should be extrapolated with caution to real urban and industrial areas, which consist of a mixture of obstacle shapes and sizes.

4.2.3. Gaussian Plume and Puff Model

The Gaussian plume and puff model is used here to illustrate the fundamental physical relations. Note that in these discussions, the term cloud is synonymous with plume or puff. For a continuous nonbuoyant plume with emission rate, $Q$ (g/s), released at height $h_e$ (m) above ground, the near-ground-level concentration, $C$ (g/m$^3$), predicted by the Gaussian plume formula is:

$$C = \left( \frac{Q}{\pi \sigma_y \sigma_z} \right) \exp\left( -\frac{(y - y_o)^2}{2\sigma_y^2} \right) \exp\left( -\frac{h_e^2}{2\sigma_z^2} \right)$$

where the lateral position of the cloud centerline is $y_o$. In the case of an instantaneous release of mass $Q_t$ at height $h_e$, the near-ground level concentration predicted by the Gaussian puff formula is:

$$C = \left( \frac{Q_t}{2^{1/2} \pi^{3/2} \sigma_x \sigma_y \sigma_z} \right) \exp\left( -\frac{(x - x_o)^2}{2\sigma_x^2} \right) \exp\left( -\frac{(y - y_o)^2}{2\sigma_y^2} \right) \exp\left( -\frac{h_e^2}{2\sigma_z^2} \right)$$

where $x_o$ is the along-wind position of the center of the cloud. The wind speed, $u$, in Eq. (9) is more precisely the local cloud advective velocity, $u_e$, at the downwind position of interest. The distance, $x_o$, in Eq. (48) is more precisely the integral with time of $u_e$ over the entire cloud trajectory [$x_o = \int u_e(t) \, dt = u_{avg} \, t$], where $u_{avg}$ is the average cloud speed over the time of travel, $t$.

The horizontal dispersion coefficients, $\sigma_x$ and $\sigma_y$, are proportional to $u^* t$ for travel times up to about fifteen minutes or more. The vertical dispersion coefficient, $\sigma_z$, is proportional to $u^* t$ for times up to about 1000 s during sunny light-wind days but only for times up to about 10 to 100 s for stable nighttime boundary layers (Hanna et al., 1996). At larger travel times, it may be necessary to account for a vertical integral scale for turbulence, $T_{z}$, as discussed below.
In most practical applications, the concentrations are predicted and assessed at certain downwind distances, $x$, rather than at travel times, $t$. Therefore, expressions such as $\sigma_y = 2u^*t$ must be converted to $\sigma_y = 2u^*x/u_{avg}$, since the variables $x$ and $t$ are related through $t = x/u_{avg}$. For nonbuoyant (passive) plumes at heights much greater than $H_r$, the local effective cloud speed, $u_e$, is nearly constant with $x$ and $t$ and is easy to determine (see the bottom panel of Figure 15). However, as mentioned earlier, for near-ground-level releases, the local $u_e$ will vary with transport time, since the cloud will steadily disperse upward and will therefore accelerate (see Figure 16). For the Kit Fox field experiments, $u_e$ was observed to increase by a factor of four or five as $x$ increased from 25 to 225 m (Hanna and Chang, 2001). As a general procedure, most hazardous gas models (e.g., HEGADAS) assume that $u_e$ equals the speed at a height of about 0.5 to 1.0 $\sigma_z$ for near-ground-level releases.

Instantaneous releases (puffs) are likely to be more affected than continuous releases (plumes) by variations in surface roughness. This is because puffs have an additional dimension, as described by the along-wind dispersion coefficient, $\sigma_x$, which is also influenced by $u^*$ and by surface roughness. The effect of roughness on maximum ground-level concentrations due to instantaneous puff releases ($Q_t$ in units of mass) near the ground can be approximated from the Gaussian puff Eq. (48) by making several assumptions:

$$C/Q_t = \left(\frac{2^{1/2}\pi^{3/2}\sigma_x\sigma_y\sigma_z}{u_{avg}/u^*}\right)^{-1} = \left(\frac{u_{avg}}{u^*}\right)^3 \left(2^{1/2}\pi^{3/2}5.2x^3\right)^{-1}$$

(49)

where it is assumed, as before, that $\sigma_x = 2u^*t = 2u^*x/u_{avg}$; $\sigma_y = 1.9u^*t = 1.9u^*x/u_e$; $\sigma_z = 1.25u^*t = 1.25u^*x/u_{avg}$; and $u_{avg}$ is the average puff advective speed over its total time of travel. Eq. (49) is valid for the maximum concentration at the center of the puff (i.e., $y = y_o$ and $x = x_o$) for a near-ground-level release (i.e., with $h = 0$), which causes the three “exp” terms in Eq. (48) to equal 1.0. Equation (49), which is valid for relatively short travel times (about 100 s or less), may be used to demonstrate two effects. First, it is clear that $C/Q_t$ will decrease as $z_o$ increases, since $u^*$ (in the denominator) will increase with $z_o$, and $u_{avg}$ (in the numerator) will decrease with $z_o$, for the same free stream or geostrophic wind speeds at the top of the boundary layer. Second, for a given puff release during nearly neutral stability and for a given $z_o$ and $x$, $C/Q_t$ will not vary with wind speed, since the ratio $u_{avg}/u^*$ will be constant. This latter effect has been seen in the Kit Fox [Enhanced Roughness Pattern (ERP) and Uniform Roughness Array (URA)] and
EPA field trials at the Nevada Test Site, where little trend was seen in 
$C/Q_t$ with $u$ for the puff releases for all three roughness types and for 
four downwind distances.

As stated above, the turbulent dispersion coefficients, $\sigma_x$, $\sigma_y$, and $\sigma_z$ 
are proportional to $u^* t$ or $u^* x/u_{avg}$ in the near-field. At larger distances, 
$\sigma_x$, $\sigma_y$, and $\sigma_z$ are observed to be less than linear in $t$ or $x$. This means that 
the travel time has exceeded the Lagrangian integral time scale, $T_{I}$, for 
the direction of concern. This behavior is seen in the equations in Table 1, which presents the Briggs formulas for $\sigma_y$ and $\sigma_z$ for rural and urban 
conditions, which are used in many regulatory dispersion models. The 
along-wind dispersion coefficient, $\sigma_x$, can be thought to be proportional 
to $\sigma_y$. Most of the equations in Table 1 involve an initial term which is 
linear in $x$ and can thought to be proportional to $u^*$, and a second term 
of the form $(1 + ax)^b$, which can be related to the term $(1 + t/2T_I)^{-1/2}$ in 
the statistical theory of dispersion (Hanna et al., 1996). From Table 1 and 
from the above mathematical expressions, it follows that $T_{I_x}$ and 
$T_{I_y}$ for the $x$ and $y$ (horizontal) components are about 1000 s or about 15 
minutes.

The vertical Lagrangian integral time scale, $T_{I_z}$, inferred from Table 1 
varyes with stability, being very large (effectively infinity) for unstable 
daytime conditions, and relatively small (a few tens of seconds) for 
stable conditions. For nearly neutral conditions and $u = 5$ m/s, it can be 
assumed that $T_{I_z}$ equals about 60 s for rural terrain and about 300 s for 
urban terrain. The effect of stability on dispersion is much more pro-
nounced in the vertical than in the horizontal directions. For stable 
conditions over rural terrain, the second term in Table 1 has a power of 
about $-1$ and the effective $T_{I_z}$ equals about 600 s for rural conditions. 
For stable conditions over urban terrain, the second term in Table 1 has 
a power of $-1/2$ and $T_{I_z}$ equals about 60 s.

The above $T_I$ values inferred from Table 1 can be combined and 
simplified for general use in urban and industrial areas as follows:

$$\sigma_y = \sigma_y t (1 + t/2T_{I_y})^{-1/2} \quad (50)$$

$$\sigma_x = \sigma_x t (1 + t/2T_{I_x})^{-1/2} \quad (51)$$

$$\sigma_z = \sigma_z w (1 + t/2T_{I_z})^{-1/2} \quad (52)$$

where

$$T_{I_y} = T_{I_x} = 1000 \text{ s} \quad (53)$$

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The above values of the integral time scales of turbulence should be used for estimating dispersion at heights above $H_r$ in urban and industrial areas. Section 4.3 suggests formulas for $T_i$ for pollutant clouds located at heights below $H_r$.

The friction velocity, $u^*$, is a key variable that can be estimated from an observation of wind speed and from knowledge of $z_o$ and $d$, which depend on the average obstacle height, $H_r$, and on obstacle shapes and spacings. Section 3.5 suggests a hierarchy of straightforward methods for estimating $z_o$, $d$, and $u^*$. If we accept an uncertainty of a factor of two in $z_o$ then, for most scenarios typical of urban and industrial areas, the rules of thumb: $z_o/H_r = 0.1$ and $d/H_r = 0.5$, can be assumed. Since the average building or obstacle height, $H_r$, is 10 m, it follows that $z_o = 0.1 \times 10 = 1$ m and $d = 0.5 \times 10 = 5$ m. More precise estimates of $z_o$ and $d$ as a function of $\lambda_f$ can be made using Eqs. (17) and (18).

As shown by the above equations, for clouds much deeper than $H_r$ (seen on the right hand side of the top panel in Figure 15), there can be a wide range of obstacle densities (say $\lambda_f$ greater than about 0.1) for which the maximum cloud concentrations will not be sensitive to the obstacle density. But, as implied earlier, a further influence on lateral dispersion will be the setting of a spatial turbulence scale by the size, geometry and specific spatial arrangement of the obstacles. This might be interpreted as a “flow-channeling” (Roberts et al., 1994). Flow channeling, however, may be more an artifact of idealized experiments than would be expected in a real urban or industrial scenario.

### 4.3. Dispersion Models for Clouds below $H_r$

In this section we consider the dispersion of material when the plume is located below $H_r$ within the urban area or industrial plant, here called the obstacle array. This situation is depicted by the regime on the left side of the top part of Figure 15. In this case the bulk of the plume is within or below the urban roughness sublayer.

Consistent with the approach in Section 3.4 and this book in general, the approach is not to consider individual buildings or structures but to model them using parameters such as $\lambda_p$, $\lambda_f$, $z_o$, or $d$. 

\[
T_{iz} = \infty \quad \text{unstable} \quad (54)
\]

\[
T_{iz} = 300 \text{ s neutral} \quad \text{and} \quad T_{iz} = 60 \text{ s stable} \quad (55)
\]
There is evidence from experiments in the laboratory and the field (e.g., Davidson et al., 1995; Macdonald et al., 1997, 1998) that the structure of a conventional Gaussian plume or puff model [see Eqs. (9) and (48)] is appropriate for the problem. Clearly the increased turbulence within the obstacle array will cause the dispersion coefficients, $\sigma_y$ and $\sigma_z$, to increase, thus tending to decrease the maximum normalized concentration, $C/Q$. It is expected that, for loosely packed obstacles where there is less of a decrease in $u$, the maximum normalized concentration, $C/Q$, may decrease as the roughness increases. But for some configurations of densely packed obstacles, where there is more of a decrease in $u$ at levels below $H_r/2$, the maximum normalized concentration, $C/Q$, may not decrease and may possibly increase under certain scenarios.

There have been some small-scale field experiments with plumes whose mass is mostly below $H_r$. For example, Macdonald et al. (1997) used movable cubes in a flat grassy field. A point source plume was released at a height of $0.5H_r$ from a position about $2H_r$ upwind of the edge of the array. The results showed little effect of the obstacles on the maximum normalized near-ground-level concentration at a given downwind position within the obstacle arrays. For increased obstacle density, the plume dispersion increased, thus tending to decrease the concentration, but at the same time, the wind speed decreased, tending to increase the concentration. The two effects roughly canceled out for this specific scenario. Davidson et al. (1995) carried out a similar small-scale field experiment and used a similar source position. A similar conclusion was reached that the maximum normalized concentration, $C/Q$, at a given downwind position was not so much different than that in the absence of the obstacles.

Several wind tunnel studies have concerned plumes released at heights less than $H_r$ in obstacle arrays. Hall et al. (1998) and Davidson et al. (1996) carried out wind tunnel experiments of plume dispersion in regularly spaced obstacle arrays, closely matching the geometry of the small scale field experiments by these same groups that were discussed above (Macdonald et al., 1997, and Davidson et al., 1995, respectively). Davidson et al. (1996) concluded that the obstacle arrays had little effect on the ground-level concentration, but this was for plume released from a point $2H_r$ upwind of the array. Hall et al. (1998) found reduction in the maximum ground-level concentrations for small $\lambda_f$, but as $\lambda_f$ was increased the concentration became constant and even began to increase for large $\lambda_f$. 

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When a conventional Gaussian plume or puff dispersion model is used [e.g., Eq. (9) or (48)], it is necessary to specify the plume advection velocity, \( u_e \), the puff average cloud speed, \( u_{avg} \), over the trajectory, the plume location, and the plume size, characterized by \( \sigma_y \), \( \sigma_z \) (and \( \sigma_x \) for short duration or transient releases). This section considers these variables and how they may be specified in terms of accessible parameters.

### 4.3.1. The Cloud Velocity, \( u_e \) or \( u_{avg} \) below \( H_r \)

In simple Gaussian plume and puff models the cloud’s local advection velocity, \( u_e \), and averaged velocity over the cloud trajectory, \( u_{avg} \), are commonly taken to be a constant equal to the wind speed at a fixed height. In slightly more complex models, \( u_e \) and \( u_{avg} \) are allowed to vary as the plume depth increases and the top of the plume extends to heights with larger wind speeds (see Figure 16). \( u_e \) and \( u_{avg} \) can be assumed to be the wind speed at the height of the cloud centerline for an elevated release, or \( u_e \) can be assumed to be the wind speed at a height of about 0.5 to 1.0 \( \sigma_z \) for a near-ground release.

The in-canopy velocity \( u_c \) that was discussed in detail in Section 3.4 is a reasonable choice for local \( u_e \) and \( u_{avg} \) for releases below \( H_r \), at least until the plume extends well above the roughness height \( H_r \). Note that \( u_c \) was also referred to as the characteristic velocity within the obstacle array. Macdonald et al. (2000) have deduced (as opposed to measured) a local plume advection velocity, \( u_e \), through an array of cubical obstacles, for various \( \lambda_f = \lambda_p \) as a function of \( x/H_r \). At a fixed downwind position, \( u_e \) decreases significantly as \( \lambda_f \) is increased, a variation generally consistent with the arguments in Section 3.4. \( u_e \) increases on average with \( x/H_r \). However, if data are considered for which much of the plume is below \( H_r \), the average advection velocities are roughly equal to \( u_c \).

Only a few Gaussian-based models account for the difference between \( u_e \) and \( u_{avg} \) and their variations with travel time or distance. Such models must use the local mass-weighted mean height of the cloud and then the wind speed at that height to obtain \( u_e \). These models then must calculate \( u_{avg} \) from its definition, \( u_{avg} = x/t = (\int u_e \, dt)/t \).

### 4.3.2. The Vertical Plume Dimension \( \sigma_z \) Below \( H_r \)

The turbulence and flow generated by the obstacles below \( H_r \) will act to increase the plume dimensions compared to the corresponding dimen-
sions in rural areas, since the turbulent velocities are larger over the rougher surface. The plume growth can be interpreted in either time or distance, since \( x = u_{\text{avg}} t \). Furthermore, for the same turbulent velocities, reducing the wind speed (i.e., \( u_{\text{avg}} \)) will act to increase the growth of the vertical plume dimension, \( \sigma_z \), with respect to \( x \).

For vertical cloud growth above \( H_r \) in an urban or industrial area, the urban curve for neutral conditions (class D) in Table 1 suggests that \( d\sigma_z/dx = 0.14 \). Experiments on the growth of the cloud dimensions at heights below \( H_r \) are few.

The Kit Fox field experiments (Hanna and Chang, 2001), clearly demonstrate the increase in the growth rate in the vertical dimension caused by the obstacles in the array. The cloud (plume and puff) depth in the array has a growth rate, \( d\sigma_z/dx \), larger than 0.16 for \( \lambda_f = 0.12 \). This growth rate is similar to the value, 0.14, mentioned in the preceding paragraph for clouds larger than \( H_r \).

In a laboratory experiment using two-dimensional bluff obstacles (infinitely high obstacles), Melia and Britter (1990) and Melia (1991) observed a linear growth rate of \( \sigma_z \) for (an equivalent) \( \lambda_f = 0.037 \) and 0.056. It is found that \( d\sigma_z/dx = 0.10 \), which is slightly less than that found for the Kit Fox experiments.

Extensive experiments by Macdonald et al. (1998) on dispersion through obstacle arrays also showed enhanced vertical growth rates for \( \sigma_z \) due to the obstacles. For \( \lambda_f = 0.16 \), \( \sigma_z/H_r = 1.3 \) at \( x/H_r = 10 \), and this might suggest a growth rate of 0.13. Similar calculations at \( x/H_r = 5 \) imply a growth rate of 0.15. However, the growth of the vertical dimension was considerably larger close to the source, declining at larger \( x/H_r \). The implication is a rapid growth rate within the first few rows of obstacles with the plume being mixed up to \( H_r \). Somewhat surprisingly, much the same conclusions can be made for \( \lambda_f \) in the range between 0.05 and 0.91, and all growth rates were larger than the growth rates for the no-obstacle case (\( \lambda_f = 0 \)).

There is slight confusion with some of these data sets concerning the position of the source in many of the experiments, and this is important in interpretation of the results. If the source is slightly upstream of the array, the plume is strongly influenced by the deceleration of the atmospheric flow as it approaches the array and the consequent increase of plume dimensions with no dilution. This is a purely kinematic effect. This was the arrangement for the experiments by Davidson et al. (1995)
and Macdonald et al. (1997), where the release point was 2 \( H_s \) upwind of the array.

The data from all the work summarized above suggest that the growth rate, \( d\sigma_z/dx \), of the vertical dimension of the plume is typically between 0.10 and 0.15 for a very wide range of \( \lambda_f (0.037 – 0.91) \) and heights below \( H_r \).

To introduce some theoretical backing, the data from Melia (1991) have been analyzed further. Both the vertical concentration profile and its along-stream development through the array are consistent with the theoretical analysis of Calder (1952). His analysis was for a uniform velocity profile and a turbulent diffusivity proportional to the distance from the ground and to a constant representative turbulence velocity (a situation close to that being considered here). As a consequence the growth rate of the vertical plume dimension at heights below \( H_s \) is:

\[
\frac{d\sigma_z}{dx} = A \frac{\sigma_w}{u_c} \quad \text{for } z < H_s \quad (56)
\]

where \( A \) is an experimentally determined constant that is calculated below.

Use can be made of the work in Section 3.4.3 where we estimate \( \sigma_w/u^* = 1.1 \) and the work in Sections 3.4.2.2 and 3.4.3 where it was found that

\[
\left( \frac{u_c}{u^*} \right) = \left( \frac{z_o}{2H_r} \right)^{-1/2} = \left( \frac{\lambda_f}{2} \right)^{-1/2} \quad (57)
\]

where Eq. (17a) is used to justify that \( z_o/H_r = \lambda_f \), which is valid for \( \lambda_f < 0.15 \).

Combining Eq. (56) and the latter term of Eq. (57), and assuming \( \sigma_w/u^* = 1.1 \), the growth rate of the vertical plume dimension is given by

\[
\frac{d\sigma_z}{dx} = 1.1A \left( \frac{\lambda_f}{2} \right)^{1/2} \quad \text{for } z < H_s \quad (58)
\]

Melia’s (1991) observations can be used to show that \( A = 0.60 \), where the average \( \lambda_f \) was 0.0465.

Extending this argument to the Kit Fox field experiments, where \( \lambda_f = 0.12 \), leads to a growth rate of \( d\sigma_z/dx = 0.16 \). For a practically large \( \lambda_f \) of 0.15, say, the growth rate would be 0.18. That is, the verti-
cal plume dimension increases so that it equals the building or obstacle height, $H_r$, in a downwind distance of about $5H_r$.

It is recommended here that Eq. (58) be used with $A = 0.60$ and with $\lambda_f$ set equal to 0.15 whenever $\lambda_f$ exceeds 0.15, as suggested by Eq. (17b).

These arguments would be aided by further experimental comparisons. However, it is certainly the case that the growth rate of the vertical plume dimension may be assumed constant and it is not smaller than the growth rate for the cloud when $\sigma_z \gg H_r$. This may be a useful operational observation. Of course, for $\lambda_f$ very small, the $\sigma_z$ should not fall below a prediction based on no obstacles (e.g., the “rural” curves in Table 1, for which $d\sigma_z/dx = 0.06$ for neutral conditions (class D) at small $x$).

### 4.3.3. The Lateral Plume Dimension $\sigma_y$ below $H_r$

The growth of the lateral plume dimension, $\sigma_y$, at heights below $H_r$ is influenced by the turbulence levels generated within the array, the spatial scale of the turbulence within the array, and a ‘topological diffusion’ related to the physical presence of the obstacles. Several experiments show that $\sigma_y$ is less strongly dependent upon the obstacle density than might be expected. Observations of dispersion within and above cube-shaped obstacles for which $\lambda_f = \lambda_p$ are presented by MacDonald et al. (2000). Close to the source, where the cloud is principally below $H_r$, $\sigma_y$ is much the same for $0.11 < \lambda_f < 0.91$ with all these results being significantly larger than for $\lambda_f = 0.0$ (i.e., a flat surface). In addition, the growth of $\sigma_y$ with $x$ is more parabolic than linear. The data can be fitted with the curve

$$\frac{\sigma_y}{H_r} = 0.50 \left(\frac{x}{H_r}\right)^{1/2} \quad \text{for } z < H_r$$

(59)

to acceptable accuracy.

Lateral dispersion within an obstacle array can be usefully analysed with a turbulent diffusion model with the turbulent diffusivity scaled on the turbulence levels and a Lagrangian integral time scale, $T_i$, which is approximated by the obstacle size, or the obstacle spacing, divided by the characteristic velocity, $u_c$. In the case where the obstacle dimension is $H_r$, then $T_i = H_r/u_c$, and the Taylor equations (50) or (51) may be used to estimate $\sigma_y$. 
At large time, \( t \), and recognizing that \( t = -x/u_c \), Eq. (50) has the solution:

\[
\sigma_y^2 = 2\sigma_x^2 \frac{H_t}{u_c} \cdot \frac{x}{u_c} \quad \text{for } z < H_t \quad (60)
\]

Or, taking the square root of Eq. (60) and dividing by \( H_t \), we obtain

\[
\frac{\sigma_y}{H_t} = \sqrt{2} \frac{\sigma_x}{u_c} \left( \frac{x}{H_t} \right)^{1/2} \quad \text{for } z < H_t \quad (61)
\]

This approach would be a good model of the experimental data at heights below \( H_t \) provided there were some justification for assuming \( \sigma_v/u_c = 0.35 \), which is required in order to give agreement with Eq. (59). The analysis in Section 3.4 indicates that typically \( \sigma_v/u^* = 1.4 \) for \( z < H_t \). This is achieved when \( u^*/u_c = 0.25 \) and this is predicted to occur when \( z_o/2H_t = 0.125 \) or \( \lambda_t = 0.25 \). Thus, if \( \sigma_v/u^* = 1.4 \) and \( u^*/u_c = 0.25 \), then \( \sigma_v/u_c = 0.35 \) and the data agree with the model.

What is difficult to understand is why the laboratory data show relatively small variations in \( \sigma_y \) over a wide range of \( \lambda_t \). This result could be explained by the square root dependence of \( \sigma_y \) on the variables in Eqs. (59) through (61). Thus a factor of five variation in \( \lambda_t \) only leads to about a factor of two variation in \( \sigma_y \). The variation is reduced even further when one considers that, as \( \lambda_t \) is increased, the integral spatial scale will reduce from \( H_t \) to a scale based on the face-to-face spacing, \( S_y \), between the obstacles. Thus, expressing Eq. (60) in the form

\[
\sigma_y^2 = 2\sigma_x^2 \frac{H_t}{u_c} \cdot x \quad \text{for } z < H_t \quad (62)
\]

we see that an increase in \( \lambda_t \) will increase \( (\sigma_v/u_c)^2 \), but \( H_t \) must be replaced with a smaller length \( S_y \). These two effects are in opposition thus further reducing the dependence of \( \sigma_y \) on \( \lambda_t \).

Macdonald et al. (1998) found that changing the aspect ratio of the obstacles has a significant effect on the lateral growth rate in his experiments with simple obstacle shapes. For example, wide flat buildings are found to be effective in increasing the lateral plume dimension. This might be mimicked by replacing the integral time scale \( H_t/u_c \) with \( W/u_c \) where \( W/H_t \) is a typical building width to height ratio.
Consequently Eq. (61) can be written as

$$\frac{\sigma_y}{H_r} = \sqrt{2} \frac{\sigma_v}{u_c} \left(\frac{x}{H_r}\right)^{1/2} \left(\frac{W}{H_r}\right)^{1/2}$$

for $z < H_r$ \hspace{1cm} (63)

and using the experiments with cubes to calibrate the model produces the result

$$\frac{\sigma_y}{H_r} = 0.50 \left(\frac{x}{H_r}\right)^{1/2} \left(\frac{W}{H_r}\right)^{1/2}$$

for $z < H_r$ \hspace{1cm} (64)

This variation with $W/H_r$ is well reflected in the experimental results of Macdonald et al. (1998). The ratio $W/H_r$ is approximately equal to the ratio $\lambda_p/\lambda_f$. Real buildings are found to have $W/H_r$ greater than 1.0.

To reintroduce the effect of $\lambda_f$ on the lateral growth rate it is recommended that

$$\frac{\sigma_y}{H_r} = \sqrt{2(1.4)} \left(\frac{\lambda_f}{2}\right)^{1/2} \left(\frac{x}{H_r}\right)^{1/2} \left(\frac{W}{H_r}\right)^{1/2}$$

for $z < H_r$ \hspace{1cm} (65)

for $0 \leq \lambda_f \leq 0.125$ and assuming $\lambda_f = 0.125$ for $\lambda_f > 0.125$. For $\lambda_f$ very small, $\sigma_y$ should not be allowed to fall below the estimate in Table 1 for dispersion with no obstacles (i.e., rural conditions). For example, for neutral (class D) conditions, the formula for rural conditions in Table 1 suggests $\sigma_y/H_r = 0.08 x/H_r$.

Hall et al. (1998) found that the plumes could suffer a significant lateral displacement when passing through regular (e.g., square or staggered) arrays of obstacles and it has been argued that this may lead to enhanced $\sigma_v$ as the wind velocity direction varies. This may be so; however, the observation is probably of little relevance for real sites with much more random geometry.

### 4.3.4. The Along-Wind Puff Dimension $\sigma_x$ below $H_r$

For transient or puff releases the released material will spread longitudinally as well as vertically and laterally, causing increased dilution [see Eq. (48)]. Thus, the along-wind dimension of the puff, $\sigma_x$, is required. The along-wind dimension is increased by turbulence, and is increased by shear dispersion due to the puff sampling regions of differ-
ent mean velocities at different heights. For flow through an industrial plant or urban area, material will enter recirculating cavities and leak out from these gradually. This puff delaying mechanism will appear as an increase in $\sigma_x$. Again, little data are available but at heights above $H_r$ over rough surfaces, Hanna and Franzese (2000) suggest that $\sigma_x = A' u^* t$, where $t$ is the time of cloud travel, $u^*$ is the friction velocity, and $A'$ is expected to range between 2 and 4. Extending the same result to below $H_r$ gives

$$\sigma_x = (A') \frac{u^*}{u_{avg}} x \quad \text{for } z < H_r$$  \hspace{1cm} (66)

or

$$\frac{d\sigma_x}{dx} = (A') \left( \frac{\lambda_f}{2} \right)^{1/2}$$  \hspace{1cm} (67)

Equation (67) is derived from Eq. (66) by using Eq. (57) and assuming $u_{avg} = u_c$.

Until further information is available, this formula is recommended with $A' = 3$. There is no guidance as to whether this correlation is applicable for only a limited range of obstacle densities. Consistency with the correlations for the vertical and horizontal dispersion coefficients and conservatism suggest that for cases where $\lambda_f$ is greater than 0.15, $\lambda_f$ should be restricted to a maximum value of 0.15 in Eq. (67).

4.3.5. The Effect of $u_c$, $\sigma_x$, $\sigma_y$ and $\sigma_z$ on the Concentration at Heights below $H_r$

As seen in Eqs. (9) and (48), the maximum normalized pollutant concentration in a continuous plume is inversely proportional to $(u_c \sigma_x \sigma_y \sigma_z)$, and in a puff is inversely proportional to $(\sigma_x \sigma_y \sigma_z)$. The analyses in the previous subsections speculate on how the obstacle array will affect the effective advection velocity, $u_c$, and the plume or puff dimensions at heights below $H_r$.

It was argued that the velocity and the dimensions at $z < H_r$ would be given by

$$u_c = u^* \left( \frac{\lambda_f}{2} \right)^{-1/2}$$
$$\sigma_x \propto \left( \frac{\lambda_f}{2} \right)^{1/2}$$
$$\sigma_y \propto \left( \frac{\lambda_f}{2} \right)^{1/2}$$

for $x < H_r$  \hspace{1cm} (68)
and the maximum normalized concentration for a continuous plume at a given $x$ would therefore be inversely proportional to $u^*(\lambda_f/2)^{1/2}$, according to Eq. (58) and (65). For a puff at heights less than $H_r$, where $\sigma_x, \sigma_y,$ and $\sigma_z$ are each proportional to $(\lambda_f/2)^{1/2}$, it follows that the maximum normalized puff concentration would be inversely proportional to $(\lambda_f/2)^{3/2}$ at a given $x$, based on these experiments.

We know that, for sparsely spaced obstacles, $u^*$ will increase with increasing $\lambda$. Thus, for sparsely spaced obstacles, the maximum normalized concentration for a continuous plume must decrease with increasing $\lambda$. That is, the more roughness obstacles, the greater the dilution and the lower the plume concentration, as we might intuitively expect.

However, the available laboratory experiments showed that $\sigma_y$ and $\sigma_z$ increase with $\lambda$ initially but then remain approximately constant at large $\lambda$. Thus, for closely spaced obstacles (large $\lambda$), $\sigma_y$ and $\sigma_z$ are constant and the continuous plume concentration will be inversely proportional to $u_c = u^* (\lambda_f/2)^{-1/2}$. For large $\lambda$, $u^*$ is constant, or even decreases with $\lambda$, in idealized laboratory experiments with obstacles of constant $H_r$. For closely spaced obstacles, the maximum normalized concentration for a continuous plume at heights near the ground must increase with increasing $\lambda$, since the wind speed is very small and the lateral plume spread is constrained. That is, the more roughness obstacles, the weaker the dilution and the greater the maximum normalized plume concentration. This counterintuitive result arises because, while the obstacles reduce the wind velocity in the array, they also interact in a way that the continuous plume sizes are not greatly affected.

This variation was evident in the data described by Hall et al. (1998), since the observed maximum normalized concentrations, $C/Q$, in a continuous plume were generally reduced by obstacle arrays of cubes compared with the case with no obstacles. The trend was for a marked reduction in maximum normalized concentrations for $\lambda$ up to $\lambda = 0.11$, little further variation up to $\lambda = 0.44$, and with a rise in $C/Q$ back toward the no-obstacle case at even larger $\lambda$. The rise in concentration at large $\lambda$ would be expected primarily for uniformly shaped laboratory cubes, and may not be seen for real-world scenarios.

For puff releases at $z < H_r$, the maximum normalized concentration, $C/Q_p$, is inversely proportional to $(\lambda_f/2)^{3/2}$. $C/Q_p$ decreases monotonically with increasing $\lambda$, though possibly more weakly at larger $\lambda$ when the dependence of the dispersion coefficients on $(\lambda_f/2)^{1/2}$ is not maintained. Additionally, the dose (i.e., the time-integrated con-
centration) will not decrease as rapidly due to the lower effective advection speed and correspondingly longer time for the cloud to dilute before it reaches a given distance, $x$.

4.3.6. Extension to Positively and Negatively Buoyant Releases below $H_f$

The reduced mean effective velocity, $u_e$, within the industrial complex or urban area will assist in the buoyant rise of the pollutant cloud. The enhanced turbulence will aid dilution of the release but also act to reduce buoyant rise. Conventional jet/plume models (Hanna et al., 1982) could easily be modified to take into account the changes in the mean velocity and the turbulence levels in their entrainment parametrizations. This approach, however, will not model the interaction of a buoyant release with any particular building.

A negatively buoyant (dense gas) release will also be influenced by the mean effective velocity, $u_e$, and enhanced turbulence within the industrial complex. The reduced $u_e$ will lead to a larger cloud in the $y$ and $z$ directions at a given $x$. The enhanced turbulence levels should act to increase the dilution of the release. These effects could be incorporated directly into conventional dense gas models, but with some uncertainty how best to introduce the turbulence levels. Until further clarifying information is available, a reasonable choice would be to incorporate the turbulence by using the friction velocity $u^*$ as the input to the model.

For large closely spaced obstacles of uniform height, where the flow is of the “skimming” type, some caution would be required in using the results. Additionally, the obstacles themselves can inhibit the gravitational spreading seen with dense-gas releases. Any model being used for such problems should be checked to see whether some account is taken for the effect of obstacles on the gravitational spreading.

4.4. Transition Methods for Clouds of Height Close to $H_f$ within the Urban Roughness Sublayer

Sections 4.2 and 4.3 addressed the regimes on the right and left ends of the top part of Figure 15; namely, situations where the cloud depth exceeds $H_f$ and situations where the cloud depth is less than $H_f$, respectively. The methods in Section 4.2 are also valid for the scenario drawn...
in the bottom part of Figure 15; namely, point source releases at heights above \( H_r \). The current section outlines methods which can assure that the solution for the ground level concentration is smoothly varying as the cloud depth increases through \( H_r \) in the middle section of the top part of Figure 15, and as the source release height, \( h_e \), in the bottom part of Figure 15 varies in the range from about 0.5 \( H_r \) to 2 \( H_r \). This is the range of heights called the urban roughness sublayer.

It has been shown above that, for clouds above and below \( H_r \), the maximum near-ground-level normalized concentration, \( C/Q \), in an urban or industrial area can be approximated given knowledge of the wind speed, \( u \), at some height, \( z \), above the surface roughness obstacle height, \( H_r \), and a measure of the obstacle density parameter, \( \lambda_f \). During nearly neutral stabilities, these parameters allow the surface roughness length, \( z_o \), the displacement length, \( d \), the friction velocity, \( u^* \), and the entire wind profile above and below \( H_r \) to be prescribed. The turbulent velocity components, \( \sigma_v \), \( \sigma_u \), and \( \sigma_w \), can then be estimated from \( u^* \), as well as the dispersion coefficients, \( \sigma_y \), \( \sigma_x \), and \( \sigma_z \), which also require estimates of the integral time scales \( T_I \).

Smooth transitions in the solutions from one regime to the other are assisted in our methodology by the fact that both regimes make use of the same (Gaussian) dispersion model, the same roughness parameters \( H_r \), \( z_o \), \( d \), and \( \lambda_f \), the same \( u^* \), and the same vertical wind profile formula. Transitions in the integral time scales, \( T_I \), are discussed below.

Given the estimates of \( z_o/H_r \) and \( d/H_r \) from Eqs. (17) and (18), the friction velocity, \( u^* \), can be estimated from Eq. (2b), given a wind speed observation or estimate, \( u \), at some height, \( z \), which is above \( H_r \). The characteristic wind speed, \( u_c \), below the obstacle heights is given by:

\[
 u_c/u^* = (\lambda_f/2)^{-1/2} \quad z < z_{int} \quad (29)
\]

which equals \((z_o/2 H_r)^{-1/2}\) for \( \lambda_f \) < 0.15. The log-linear wind profile [Eq. (2b)] is assumed to apply down to a height, \( z_{int} \), such that \( u(z_{int}) = u_c \). The height \( z_{int} \) is calculated by setting Eqs. (2b) and (29) equal to each other and solving for \( z_{int} \), where the two \( u \) solutions are equal. For obstacles with large spacings (i.e., \( \lambda_f \) approaching zero), \( z_{int} \) can become much less than \( H_r \) and iteration may be required to estimate \( u_c \).

Because of the variability of the obstacle heights at real sites, the determination of the “roughness element height” or the “average building height,” \( H_r \), will produce the greatest uncertainty in application. Also for some situations with densely packed buildings with a few
imbedded very tall buildings, the surface drag and surface roughness length may be determined by the upper ranges of the distribution of obstacle heights rather than the mean $H_r$.

As the source height and the cloud height vary across the urban roughness sublayer, the turbulent velocities are assumed to be given by the following relations at all heights above $H_r$: $\sigma_u/u^* = 2.4$, $\sigma_v/u^* = 1.9$, and $\sigma_w/u^* = 1.25$. These basic constants are discussed in most boundary layer textbooks such as Stull (1997) and have been verified at heights near to and slightly below $H_r$ by Rotach (1999) and Roth (2000). The authors often report a peak in turbulence at or just above $H_r$, but this peak is usually only 20 or 30% greater than the values at heights of about 2 $H_r$, and the differences are ignored in the simple model presented here. Furthermore, limited data discussed in the previous section suggest that the turbulent velocities may be slightly less at heights less than $H_r$. It is expected that current research is likely to improve these estimates of turbulent velocities below $H_r$.

The turbulent integral time scales, $T_I$, for the situations with cloud depth exceeding $H_r$ were discussed in Section 4.2 and some simple estimates were suggested in Eqs. (50) through (56). For the lateral component [see Eq. (50)], the following equation illustrates how $T_{Iy}$ is used:

$$\sigma_y = \frac{\sigma_y t}{\left(1 + t/2T_{Iy}\right)^{1/2}} = \frac{2u^* \left(x/u_{avg}\right)}{\left(1 + x/2u_{avg}T_{Iy}\right)^{1/2}}$$  \hspace{1cm} (69)

Note that the relation $\sigma_v = 1.9 u^*$ is rounded to $2u^*$. The solution is linear in $t$ for $t < T_{Iy}$, and approaches a $t^{1/2}$ relation for $t > T_{Iy}$. Eq. (53) suggests that $T_{Iy}$ (and $T_{Ix}$) equals 1000 s (or about 15 minutes), implying that $\sigma_y$ will be linear in $t$ or $x$ for travel times less than about 15 minutes or travel distances less than about 5 km (assuming an average cloud advective speed, $u_{avg}$, of about 5 m/s).

For the vertical component, the integral time scale, $T_{Iz}$, for clouds dispersing above $H_r$ is very large for daytime unstable conditions, is 300 s for nearly neutral conditions, and is 60 s for nighttime stable conditions [Eqs. (54) through (56)].

For clouds below $H_r$, it has been suggested by Hall et al. (1997) that $T_{Ix} = T_{Iy} = T_{Iz}$ and are proportional to about $H_r/u_c$ or $S_y/u_c$, where $S_y$ is the crosswind obstacle spacing. It is argued that the horizontal eddy sizes below $H_r$ can be no larger than the spaces between the obstacles.
For typical spacings and advective speeds in industrial and urban sites, these time scales range from a few seconds to a few minutes.

For the transition regime in the urban roughness sublayer, where cloud depth is approximately equal to $H_r$, or where the point source release is close to $H_r$, the following methods are recommended:

Case 1, where the cloud is released near the ground and grows so that its depth exceeds $H_r$. Use the “below $H_r$” $\sigma_x$, $\sigma_y$, and $\sigma_z$ prediction methods until $\max(\sigma_z, h_e)$ exceeds $H_r$. Then use the “above $H_r$” $\sigma_x$, $\sigma_y$, and $\sigma_z$ prediction methods but implementing a virtual source procedure once $\max(\sigma_z, h_e)$ exceeds $H_r$. A different virtual source is used for each of the three components (i.e., $x$, $y$, and $z$). Hanna et al. (1996) discuss the virtual source methodology, which is straightforward and is illustrated in Figure 17. Considering the lateral component, $\sigma_y$, the vertical source method begins with the $\sigma_y(x)$ estimated by the “below $H_r$” formulas at the transition distance, and then calculates the upwind virtual distance

![Diagram of virtual source concept](image)

FIGURE 17. Schematic diagram of virtual source concept. It assumed that $\sigma_y(x)$ for the dispersion model for the cloud at heights below $H_r$ can be set equal to $\sigma_y(x + x_v)$ for the dispersion model for the cloud above $H_r$. The cloud is released near ground level at the actual source location. Once the cloud disperses above $H_r$, the subsequent $\sigma_y$ values are calculated as if the source were at the virtual source location, which is a distance $x_v$ behind the actual source.
from the actual source, \( x_v \), required so that \( \sigma_y (x + x_v) \) from the “above \( H_r \)” formula equals \( \sigma_y (x) \) from the “below \( H_r \)” formula.

**Case 2**, where the cloud is released from a point or with very small initial dimensions at an elevation close to \( H_r \). Calculate \( \max (\sigma_z, h) \). If \( \max (\sigma_z, h) \) is greater than \( H_r \), use the “above \( H_r \)” \( \sigma_x, \sigma_y, \) and \( \sigma_z \) prediction methods. If \( \max (\sigma_z, h) \) is less than \( H_r \), use the “below \( H_r \)” \( \sigma_x, \sigma_y, \) and \( \sigma_z \) prediction methods, with a transition to the “above \( H_r \)” values employing the virtual source method as discussed above.

These two approaches are appropriate for calculating ground level concentrations. It is important to point out that there have not been many measurements of turbulence and dispersion in real urban and industrial sites and there may be a need to revise the method as additional data become available.

### 4.5. Summary and Recommendations

In this section we summarize some of the more important results of this chapter and offer recommendations.

#### 4.5.1. Dispersion Models for Clouds Extending above \( H_r \)

1. Many operational models exist for this scenario. These models often require as input flow parameters such as \( z_0, d, \) and \( u^* \) and methods for determining these parameters have been provided in Chapter 3.
2. The above statement holds for passive, heavy, and light gas releases.
3. For passive releases (both puffs and plumes) at any height we have provided the Gaussian model solutions for concentration in Eqs. (9) and (48) in terms of the dispersion coefficients. We have also provided correlations for the dispersion coefficients in terms of \( u^* \) and (in the far-field) the integral time scale \( T_I \) [see Eqs. (50) through (56)].

#### 4.5.2. Dispersion Models for Clouds Released above or Near \( H_r \)

1. No distinction is made between this scenario and that addressed in 4.5.1. The implication of this choice is that the flow in which
the release is dispersing is that determined by the underlying roughness. This will be a less valid assumption for releases well above $H_r$ and when the release is close to the upwind edge of the roughness but this would be an unlikely situation.

3. The above statement holds for passive (neutral) and buoyant gas releases. It is likely to hold for heavy gas releases until the cloud trajectory descends well inside the roughness obstacles.

4.5.3. Dispersion Models for Clouds below $H_r$

1. Currently there are only a few preliminary operational models for this scenario and they have been subjected to limited testing with field observations. The analysis and arguments for this scenario are novel.

2. There is evidence that a Gaussian model is appropriate for this case. This requires specification of an advection velocity and correlations for the dispersion coefficients.

3. The correlation for the advection velocity is given by Eq. (29) and those for the vertical, lateral and longitudinal dispersion coefficients by Eqs. (58), (65), and (67), respectively.

4. The correlations show that, on the centerline of a continuous plume, at a fixed downwind distance, the maximum normalized concentrations initially decrease with increasing roughness but eventually become constant and then may increase slightly for very large roughness. For puffs the correlations predict a monotonic decrease in concentration with increasing roughness.

5. All the above is applicable for passive and light gas releases. For heavy gas releases a modification would be required to existing operational models to account for changes to the velocity profile within the roughness obstacles.

6. Recommendations are provided in Section 4.4 to accommodate the transition in the urban roughness sublayer for clouds growing from heights below $H_r$ to heights above $H_r$.

4.5.4. Dispersion Models for Scenarios where the Upwind and Downwind Roughness Is Different

The approach that has been adopted here has been to only include the effects of roughness downwind of the source. Thus, the roughness to be
considered is a weighted average of the roughness between source and receptor [see Eq. (19a)]. This approach may lead to concentration overprediction close to the source for the situation where the source is near the downwind edge of the urban or industrial site. In that situation, the extreme rough surface upwind of the source would not be accounted for.

4.5.5. Dispersion Models for Clouds Released Upwind of the Roughness and Traveling into and Through the Roughness

The approach that has been adopted here has, again, been to consider the roughness between the source and receptor, and by implication to use an advection velocity determined by this roughness. This is a very simplistic model of the complex flow as the atmospheric boundary layer impinges upon a finite area of increased roughness.