CHAPTER 6

Air Pollution Dispersion

6.1 Introduction

Air pollution dispersion models are used to predict the concentrations of emissions as a function of distance from the discharge source. There are two main types of variables – meteorological and source conditions. Meteorological variables include wind speed and direction, atmospheric stability, and temperature. Source conditions include location, elevation, emission rate, velocity, temperature, and pollutant (PM, NO_x, SO_x, VOC, HAP, …). Models incorporate some or all of these variables to estimate the amount of mixing a plume undergoes as it is moves from the source. Mixing has many causes: diffusion, wind speed and direction changes (tortuosity), friction within the boundary layer, and turbulence. Advanced models can include effects from local terrain and buildings, and changes due to chemical reactions, surface deposition, and washout by rain or snow.

Dispersion models are used by regulating agencies to determine if a new or modified emission will have an impact on ambient air quality. Not all emission sources are required to run dispersion models. State or national guidelines define which sources need to model their emissions. Identification of sources that are required to model will depend on the type of emission, the amount of emissions of a particular substance or group of substances, or the current ambient air conditions. Also, not all sources that are required to perform models need to install pollution control equipment. The decision depends on the results of the modeling.

The US EPA and state regulatory agencies require emission modeling for major sources. Major sources (such as fossil fuel-fired power plants, kraft paper mills, smelters, steel mills and oil refineries) are those that have the potential to emit 100 ton/ yr or more of any one pollutant regulated by the Clean Air Act. Other facilities that can potentially emit 250 ton/yr. or more of any combination of pollutants are also classified as major sources. Potential emissions assume that the source operates at maximum capacity for a full year. These values may be modified if the source is in a region that has pollutants that exceed the National Ambient Air Quality Standards (NAAQS), or if the source is near a protected area (recreational area, national park, or wilderness area). Different limits may also be imposed under Prevention of Significant Deterioration rules (see chapter 3.2.4 New Source Review for more details).

6.2 Modeling

There are two types of models: screening level models and refined models. Initially, a screening level model is used. These models use relatively simple estimation techniques and assumptions that tend to overestimate pollutant concentrations downwind. If the screening model suggests there may be an air quality impact, then refined models are used to reassess the emission. Results from such models are used to justify the requirement of emission reduction, site relocation, or another appropriate action.

There are four types of screening level models: Gaussian, numerical, statistical, and physical - **Gaussian** models assume a single point source plume that follows a Gaussian or normal probability distribution equation. This type of model system is straight-forward in terms of calculations (steady state, non-reactive, single component) and is the most widely used. **Numerical** models are used for area sources and may include chemical reactions. They also allow multiple constituents to be included and modeled simultaneously. They relax many of the assumptions used in the Gaussian model, but require much more detailed information. **Statistical** models are used to allow modeling when the system information is poorly known. Correlations and approximation methods replace the detailed knowledge required in other models. **Physical** models involve the construction of scaled models to allow physical observations of fluid flow within the model system. This method can model very complex terrain or building effects, but it is very time consuming.

The choice of screening level model depends on the type of pollutants being emitted, the complexity of the source, the type of topography surrounding the facility, and the type and amount of known information. Many pollutants react within ambient air to transform into different forms - particles can coagulate (fluid to solid), agglomerate (two or more dissimilar solids join to form a larger solid), conglomerate (two or more similar solids join to form a larger solid), or dissolve into water; NO_x and VOCs photo-react to form ozone; SO_x and NO_x can react with water to form acid gases and particles. Source complexity, such as multiple point sources, line sources, or area sources complicate calculations and require greater knowledge of source type and geometry. Topography issues, such as the presence of a river or mountain valley, changes in land use (rural to urban transformations), hills, and large buildings can bias the local weather patterns by constraining local atmospheric movement. Elevated terrain heights downwind may experience higher pollutant concentrations since they are closer to the plume centerline. Proposed sources in complex environments may be difficult to precisely model, and the model may need to improvise for missing information by using correlations, regional approximations, and history match methods.

A detailed discussion of each model is beyond the scope of this text. The most commonly used model system, the Gaussian dispersion model, serves to introduce the concepts. Additional information about other models may be found in sources such as (US-EPA, 2011), (EEA, 2007), and (Moussiopoulos, et al., 1996).

6.3 Gaussian Model

The Gaussian model equation is based on a solution to the Advection Dispersion Equation (ADE):

6.1
$$\frac{\partial C}{\partial t} = -u_i \frac{\partial C}{\partial x_i} + \frac{\partial}{\partial x_i}\left[D_{ij}\frac{\partial C}{\partial x_j}\right]$$

Where: C = concentration at any point in the system,
t = time,
x_i = position vector (x, y, z),
u_i = velocity vector (v_x, v_y, v_z), and
D_{ij} = dispersion tensor, a 3 x 3 tensor describing mixing in each direction caused by forces acting in each direction.

The ADE is used to describe the transport of a contaminant due to both advection (transport due to the bulk motion of the fluid) and dispersion (transport due to mixing motions such as diffusion, flow path tortuosity, and turbulence). The solution includes the following assumptions:

1. Steady state, $\partial C / \partial t = 0$,
2. Advection occurs only in the x-direction ($u_i = u_x$) and is constant,
3. Advection has a much larger effect than dispersion, and
4. Contaminant does not react or otherwise change form.

Assumption 2 allows all the non-diagonal dispersion terms to be set to zero. Assumption 3 allows the D_{xx} term to be ignored, which implies dispersion is zero in the x-direction. Applying these assumptions simplifies the ADE to:

6.2 $$-u_x \frac{\partial C}{\partial x} + D_{yy} \frac{\partial^2 C}{\partial y^2} + D_{zz} \frac{\partial^2 C}{\partial z^2} = 0$$

Applying the additional conditions:

$C = C_0$ at (x=0, y=0, z=0) = 0 [contaminant is discharged at a constant value from the point (0, 0, 0)]

$C = 0$ as x, y, z →∞ [contaminant has background concentration of zero]

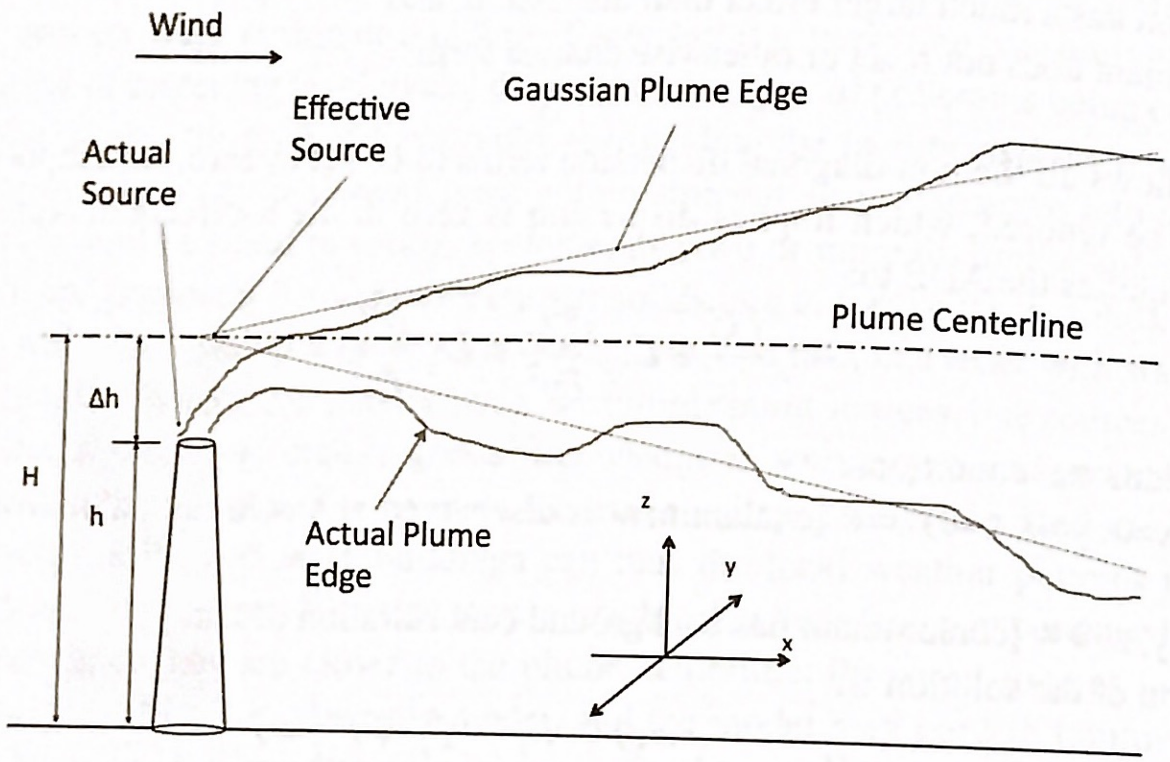
The general form of the solution is:

6.3 $$C(x,y,z) = \frac{Q}{u} \frac{F_y}{\sigma_y \sqrt{2\pi}} \frac{F_{z1} + F_{z2} + F_{z3}}{\sigma_z \sqrt{2\pi}}$$

Where: C = downwind, steady state concentration [µg/m3],
x = distance downwind from source [m],
y = horizontal distance from plume centerline [m],
z = vertical distance from plume centerline [m],
Q = emission rate [µg/s],
u = wind speed at effective stack height, always in x direction [m/s],
σ_y = mixing length in horizontal direction [m],
σ_z = mixing length in vertical direction [m],
F_y = horizontal mixing (see equation 6.5), and
F_z = vertical mixing (see equation 6.7).

Figure 6-1 provides a sketch of a Gaussian model from a stack source. This model assumes that the wind speed is constant in direction and magnitude, that wind speed is not a function of elevation, the plume has a Gaussian or normal distribution, the emission rate (Q) is continuous and constant, that there are no other emission sources, and there are no additional sources of turbulence (nearby buildings, for example). While the assumptions are limiting, these models still provide an order of magnitude estimate and allow identification of when and where a potential problem may occur. The Gaussian models are quite conservative in that they overestimate down-wind ground level concentrations by factors of 2-3 or even 10 fold. They are excellent first models to determine if the source could be a problem because it is quick and easy to use and provides an overly conservative estimate.

FIGURE 6-1. Stack-Based Emission Source and Gaussian Model Approximation of Plume.



The mixing lengths, σ_y and σ_z, are functions of downwind distance and atmospheric stability (Pasquill stability class, section 5.7.2). The horizontal mixing length, σ_y, can be read from Figure 6-2 (easiest) or calculated for rural areas using equation 6.4 and Appendix IV Table 1, or for urban areas use the formulas in Appendix IV Table 2. These equations originate from experimental observation of measurements over flat, rural terrain (Turner, 1994).

6.4
$$\sigma_y = 465.116 * x * \tan\left[0.0174533(a - b * \ln[x])\right]$$

Where: x = distance downwind in km,
a and b = rural area parameters, values are given in appendix IV Table 1, and
tan = tangent function, with argument in radians.

Horizontal mixing is symmetric about the plume centerline:

$$F_y = \exp\left(-\frac{y^2}{2\sigma_y^2}\right)$$

6.5

The horizontal mixing value increases with downwind distance, increases with increasing atmospheric instability, and is generally larger in urban environments.

The vertical mixing length, σ_z, can be read from Figure 6-3 or calculated for rural areas using equation 6.6 and Appendix IV Table 3, or for urban areas use the formulas in Appendix IV Table 4. Note that Figure 6-2 and Figure 6-3 were generated using these equations, yielding good agreement between the two methods. Also note that the equations have greater precision, but both methods have the same accuracy (±25%).

$$\sigma_z = cx^d$$

6.6

Where: x = distance downwind in km, and
c and d – rural area parameters, values given in Appendix IV Table 3.

FIGURE 6-2. Horizontal Mixing Length for Rural and Urban Areas as a Function of Pasquill Atmospheric Stability Class. The data for this figure is from the ISC3 dispersion model (US-EPA, 1995).

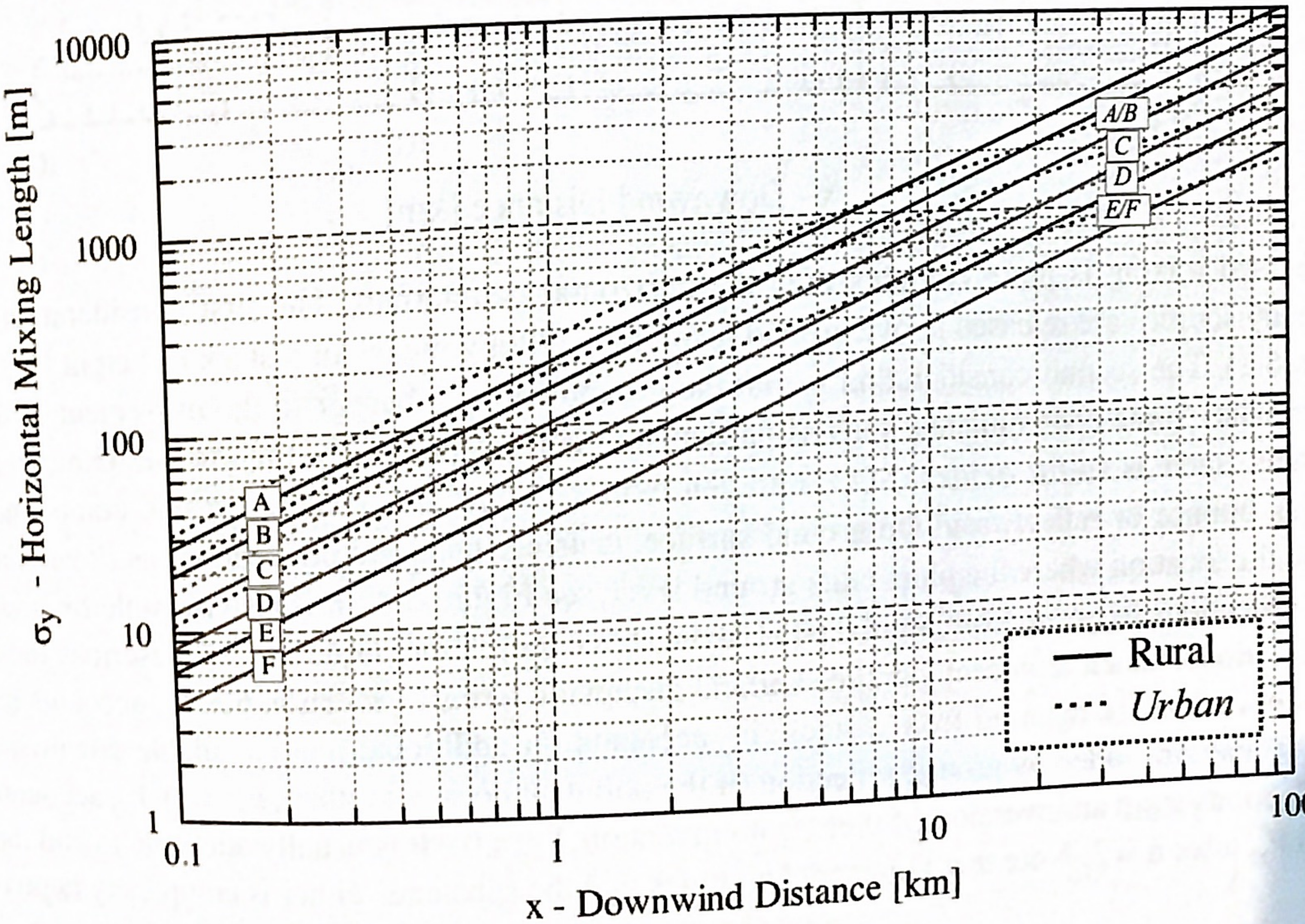
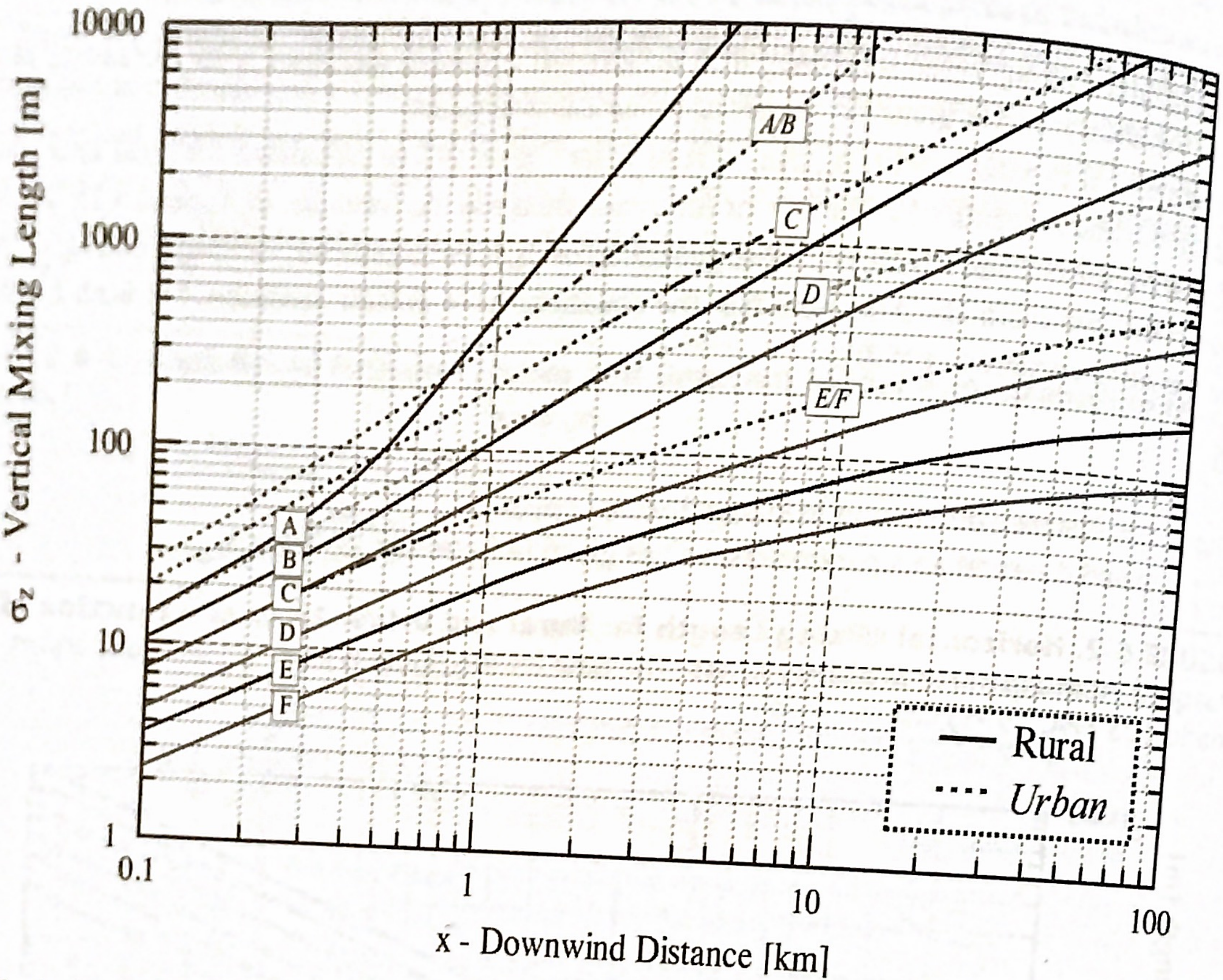
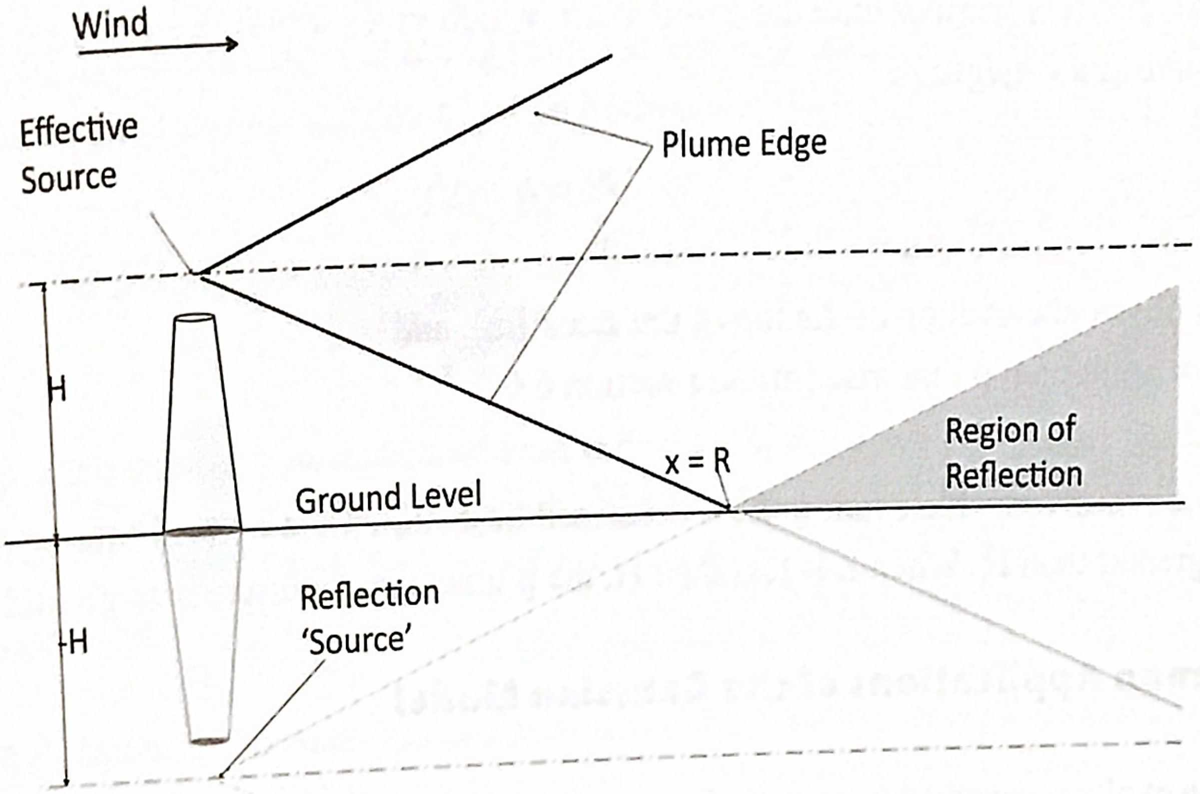


FIGURE 6-3. Vertical Mixing Length for Rural and Urban Areas as a Function of Pasquill Atmospheric Stability Class. The data for this figure is from the ISC3 dispersion model (US-EPA, 1995).



Vertical mixing is more complex than the horizontal counterpart. The first consideration is that many sources are released above ground level, typically by means of a stack of height H (see Figure 6-1). The second consideration is that the ground forms a barrier to the movement of the contaminant. Some contaminants, such as particulate matter deposit onto the ground. Other contaminants, such as sulfur oxides (SO_x), nitrogen oxides (NO_x), and volatile organic compounds (VOCs), bounce or reflect from the ground surface, causing increased concentrations downwind beyond the location where the plume hits ground level, see Figure 6-4. It is also possible for additional reflections to occur from an inversion layer above the plume. Equation 6.7 describes these considerations, which represent the three vertical dispersion terms in equation 6.3. F_{z1} accounts for the material directly released from a stack. F_{z2} accounts for additional mass available downwind from the material added by ground reflection (if the pollutant does not reflect, $F_{z2} = 0$). F_{z3} accounts for reflections from an inversion (if there is no inversion, $F_{z3} = 0$). It is usually adequate to end the sum in F_{z3} after $n = 2$. Note that this model assumes that the substance either is completely deposited or completely reflects. Actual materials do some of each. Particles can be re-entrained into the atmosphere by surface winds. Gaseous compounds may adsorb onto moisture on the ground or plants. More information allows for better modeling, but adds complexity that is rarely useful for a screening level model.

FIGURE 6-4. Change in Downwind Concentration due to the Ground as a Reflection Source. Ambient air concentrations downwind of x=R are enhanced as the material reflects from the ground back into the air above ground level.



$$F_{z1} = \exp\left(-\frac{(z-H)^2}{2\sigma_z^2}\right)$$

$$F_{z2} = \exp\left(-\frac{(z+H)^2}{2\sigma_z^2}\right)$$

6.7

$$F_{z3} = \sum_{m=1}^{n} \exp\left(-\frac{(z-H-2mL)^2}{2\sigma_z^2}\right) + \exp\left(-\frac{(z+H+2mL)^2}{2\sigma_z^2}\right) + \exp\left(-\frac{(z-H+2mL)^2}{2\sigma_z^2}\right) + \exp\left(-\frac{(z+H-2mL)^2}{2\sigma_z^2}\right)$$

Where: H = effective stack height [m], and
L = elevation of inversion above ground level, not shown in Figure 6-4 [m].

Note: F_{z3} is only applied when the plume is expected to interact with an inversion layer. The plume will 'bounce' or reflect off the layer similar to how it reflects from the ground.

The vertical position of the plume centerline is higher than the physical height of the stack due to two characteristics of the emissions: it is launched with some vertical velocity as it exits the stack (momentum), and it is warmer than the ambient air, which gives it buoyancy. A simple description of this *effective stack height* is:

6.8
$$H = h + \Delta h$$

Where: h = physical elevation of the top of the stack [m], and
Δh = additional plume rise [m], see section 6.6.

Determination of inversion elevation (L) is described in section 5.7.4 – Mean Mixing Depth. Also, L must be greater than H. When L is less than H, the plume can not disperse to ground level.

6.4 Common Applications of the Gaussian Model

This section explores several common applications of the Gaussian model. Each case describes possible scenario(s) and the form of the applicable Gaussian model solution. All calculations assume one hour averaging time as suggested by the US EPA models.

6.4.1 Case 1. Ground Level Source

This scenario occurs from emissions at ground level, such as open pit burning, evaporation from an open tank or pond, or slow release from a spill or leak. Downwind ground level concentrations are given by combining equations 6.3, 6.5, and 6.7 while setting H =0:

6.9
$$C(x,y,z) = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \exp\left(-\frac{z^2}{2\sigma_z^2}\right)$$

This result should be multiplied by a factor of 2 if the emission material reflects from the ground surface rather than being deposited (in which case $F_{z2} = F_{z1}$ rather than zero for the no reflection case.

■ ***Example 6-1.***

Calculate the PM_{10} concentration 500 m downwind from the open burning of 100 pounds per hour of wood using a ground level wood stove. The weather is overcast with a wind speed of 3 m/s in a rural area.

Solution:

Assume that PM_{10} do not reflect so use equation 6.9 as is, with x = 500m, y = 0, and z = 0. Determine σ_y and σ_z from Figure 6-2 and Figure 6-3 at x = 0.5 km. Use atmospheric stability class D because the weather is overcast. Obtain Q from the emission factors in Appendix 3 which shows PM emissions are 30.6 pounds per ton of wood burned.

$$C(500,0,0)=\frac{694.6x10^{6}\,\frac{\mu g}{hr}}{2\pi\left(3\frac{m}{s}\right)(35m)(18m)}\frac{hr}{3600s}=16.3\frac{\mu g}{m^{3}}$$

It should be noted that the assumption of zero reflection is not completely true. Smaller particles can be returned to the atmosphere by a slight breeze. We use this assumption to model certain behaviors, realizing that the final answers are accurate within +/- 25% - 50%.

6.4.2 Case 2. Elevated Source

This scenario is for non-reflecting pollutants, such as PM or vapors that are readily adsorbed or absorbed by the ground, such as SO_x over open water. Downwind concentrations are given by combining equations 6.3, 6.5, and 6.7 and ignoring F_{z2} and F_{z3}:

6.10 $$C(x,y,z)=\frac{Q}{2\pi u\sigma_y\sigma_z}\exp\left(-\frac{y^2}{2\sigma_y^2}\right)\exp\left(-\frac{(z-H)^2}{2\sigma_z^2}\right)$$

Large particles (diameter > 10 μm) settle quickly due to gravity and thus are transported to the ground faster than this equation predicts. A modification of H can help account for this difference:

6.11 $$C(x,y,z)=\frac{Q}{2\pi u\sigma_y\sigma_z}\exp\left(-\frac{y^2}{2\sigma_y^2}\right)\exp\left(-\frac{\left(z-\left(H-\frac{v_t x}{u}\right)\right)^2}{2\sigma_z^2}\right)$$

Where: v_t = terminal velocity of the particle [m/sec], see figure 7.8 in section 7.3.1 Particle Motion Due to Gravity.

Example 6-2.

Repeat the calculation from Example 6-1, except with the source elevated by a chimney 10 m in effective height.

Solution:

Use equation 6.10 with H = 10m and the remaining data from Example 6-1.

$$C(500,0,0)=\frac{694.6x10^{6}\,\frac{\mu g}{hr}}{2\pi\left(3\frac{m}{s}\right)(35m)(18m)}\exp\left[-\frac{(0-10m)^{2}}{2(18m)^{2}}\right]\frac{hr}{3600s}=13.9\frac{\mu g}{m^{3}}$$

The chimney reduces the concentration at 500m by about 15% although it does not change the total amount of PM emitted by this source.

6.4.3 Case 3. Elevated Source with Reflection

This scenario is for reflecting pollutants, such as SO_x, NO_x, CO, and VOCs that do not interact with the ground. Downwind concentrations are given by combining equations 6.3, 6.5, and 6.7 and ignoring F_{z3}:

$$C(x,y,z)=\frac{Q}{2\pi u\sigma_y\sigma_z}\exp\left(-\frac{y^2}{2\sigma_y^2}\right)\left[\exp\left(-\frac{(z-H)^2}{2\sigma_z^2}\right)+\exp\left(-\frac{(z+H)^2}{2\sigma_z^2}\right)\right] \quad 6.12$$

Example 6-3.

55 g/s of NO_x is emitted in an urban area from a stack of 35m (effective height). The weather is sunny with a wind speed of 4 m/s at the stack height. Graph the downwind centerline concentration from 0.5 to 10 km.

Solution:

NO_x is a reflecting compound so use equation 6.12 to determine the concentrations. The solution must allow x to vary from 0.5 to 10 km, and set y = 0 and z = H which follows the downwind centerline of the plume. Q and u are given. The atmospheric stability is found using Figure 6-2 and Figure 6-3 to determine σ_y and σ_z. To find atmospheric stability we need to find the wind speed at

10 m and estimate the daytime insolation condition. Use Table 5-5, we initially guess the stability to be class B, which allows choosing the stability exponent p = 0.15 (Class B, urban).

$$u_{10m} = u_{35m}\left(\frac{10}{35}\right)^{0.15} = (4.0\frac{m}{s})(0.285)^{0.15} = 3.3\frac{m}{s}$$

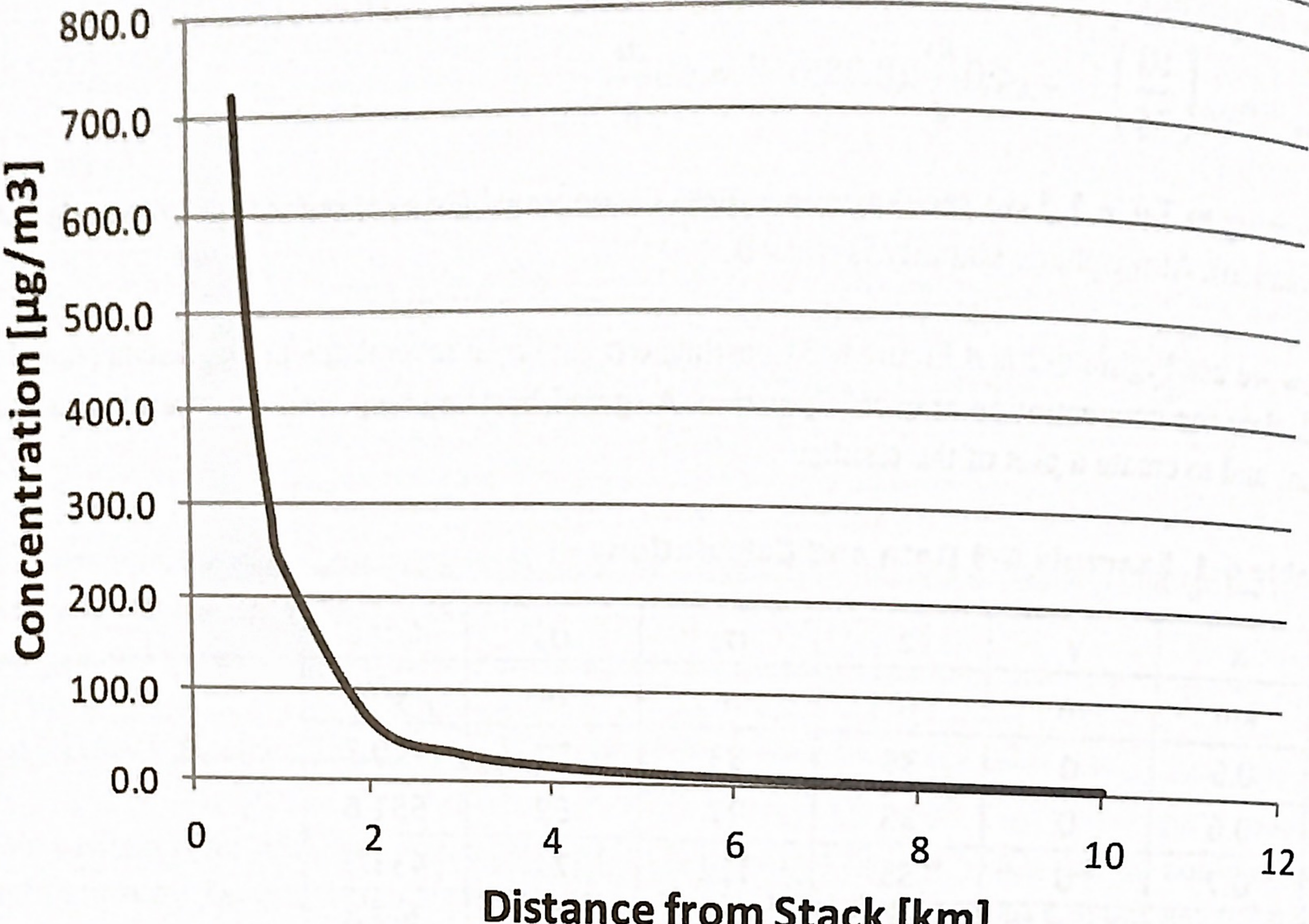
Returning to Table 5-5 we see our initial guess is confirmed (wind speed 3.3 and strong daytime insolation). Atmospheric stability is class B.

Now we use Figure 6-2 and Figure 6-3 to estimate σ_y and σ_z at several downwind distances, and to calculate the concentration at each x position. A spreadsheet can help with the repetitive calculations and to create a plot of the results:

Table 6-1. Example 6-3 Data and Calculations.

x	y	z	σ_y	σ_z	Conc
km	m	m	m	m	$\mu g/m^3$
0.5	0	35	83	51	720.3
0.6	0	35	97	62	551.6
0.7	0	35	112	74	433.5
0.8	0	35	126	86	347.8
0.9	0	35	140	97	284.1
1	0	35	154	109	235.8
2	0	35	286	234	64.1
3	0	35	409	365	29.1
4	0	35	527	500	16.5
5	0	35	641	639	10.7
6	0	35	752	780	7.4
7	0	35	861	924	5.5
8	0	35	967	1070	4.2
9	0	35	1071	1218	3.4
10	0	35	1174	1367	2.7

FIGURE 6-5. Downwind, Centerline Concentration Profile for Example 6-3.



6.4.4 Case 4. Ground Level Concentrations from Elevated Source with Reflection

This subset of solutions quantifies the impact an emission may have on the local air. It focuses on concentrations at ground level, where people, animals, and plants are. This case is also used to determine the impact a source has on ambient air quality. Downwind ground level concentrations are given by:

6.13 $$C(x,y,z)=\frac{Q}{2\pi u\sigma_y\sigma_z}\exp\left(-\frac{y^2}{2\sigma_y^2}\right)\left[2\exp\left(-\frac{(H)^2}{2\sigma_z^2}\right)\right]$$

Note that the terms F_{z1} and F_{z2} are combined since $(z-H)^2$ and $(z+H)^2$ are equal when $z = 0$. *Do not use this equation for any other elevation.*

■ *Example 6-4.*

SO_x are emitted at a rate of 125 g/s from a stack with an effective height of 70 m. The atmospheric stability is class C and the wind speed at 10 m is 5 m/s in a rural area. Determine the downwind ground level concentration at x = 1 km and y = 100m.

Solution:

This example is solved using equation 6.12 with x=1 km, y=100, and z =0 or equation 6.13 with x=1 km, y=100. The wind speed must be corrected to the effective stack height using equation 5.12 and p=0.1 from Table 5.3. Then determine σ_y and σ_z from Figure 6-2 and Figure 6-3 for rural areas at x=1 km.

$$u_{70m} = u_{10m}\left(\frac{70}{10}\right)^{0.1} = (5.0\frac{m}{s})(1.215) = 6.1\frac{m}{s}$$

$$C(1000,100,0) = \frac{125x10^{6}\,\frac{\mu g}{s}}{2\pi\left(6.1\frac{m}{s}\right)(100m)(60m)}\exp\left(-\frac{100^{2}}{2(100m)^{2}}\right)$$

$$\left[\exp\left(-\frac{(0-(70m))^{2}}{2(60m)^{2}}\right)+\exp\left(-\frac{(0+(70m))^{2}}{2(60m)^{2}}\right)\right] = 334\frac{\mu g}{m^{3}}$$

■ *Example 6-5.*

Use the data from Example 6-4 to create an isopleth (concentration contour) map of downwind SO_x concentrations within boundaries of (0<x<3000m, 0<y<400m, with z=0).

Solution:

This problem is best solved using a spreadsheet program with graphing capability. The plot is generated by calculating the concentration at several downwind locations. Determine σ_y and σ_z from Figure 6-2 and Figure 6-3 or equations 6.4 and 6.6 for rural areas at each x-distance. Concentrations are then calculated using equation 6.12. Note that this equation is symmetric about the centerline (y = 0), so the solution at y = 100 m is the same as y = -100 m. Therefore, only the positive y-axis is shown.

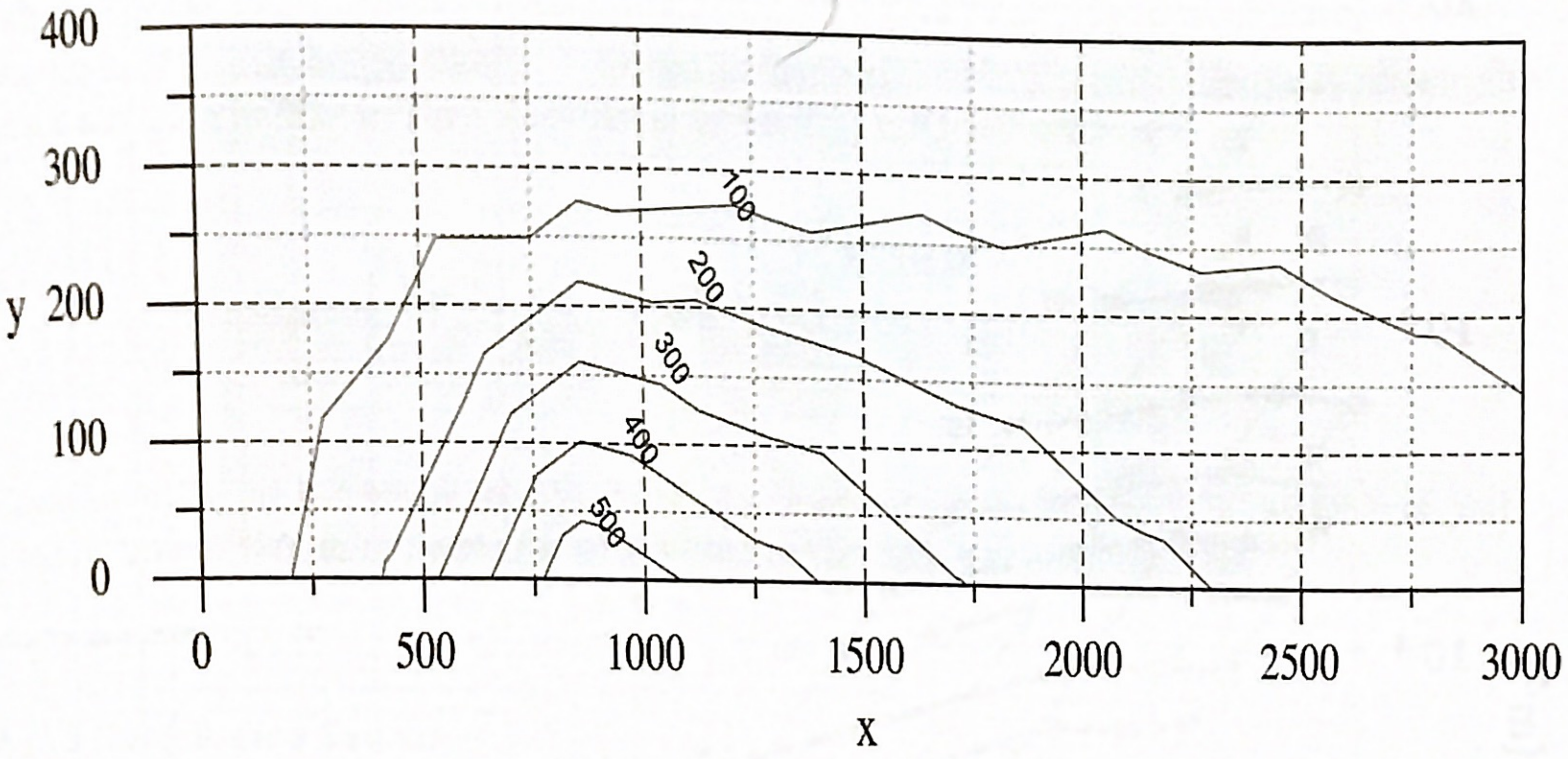
Table 6-2. Example 6-5 Data and Calculations.

Q =	125	g/s
u =	5	m/s at 10 m
u at H =	6.1	m/s at 70 m
H =	70	m
Atm Class =	C	

x [m]	y [m]	σ_y[m]	σ_z [m]	C [ug/m3]
0	0	1	1	0.0
250	0	29	17	3.3
500	0	55	32	358
750	0	79	47	577
1000	0	103	61	537
3000	0	279	167	128
250	100	29	17	0.0
500	100	55	32	68
750	100	79	47	261
1000	100	103	61	336
3000	100	279	167	120
250	200	29	17	0.0
500	200	55	32	0.5
750	200	79	47	24
1000	200	103	61	82
3000	200	279	167	99
250	400	29	17	0.0
500	400	55	32	0.0
750	400	79	47	0.0
1000	400	103	61	0.3
3000	400	279	167	46

This data can be used to generate a surface or contour plot. Note that σy and σz are not defined at x=0, so all concentrations are set to zero at this location.

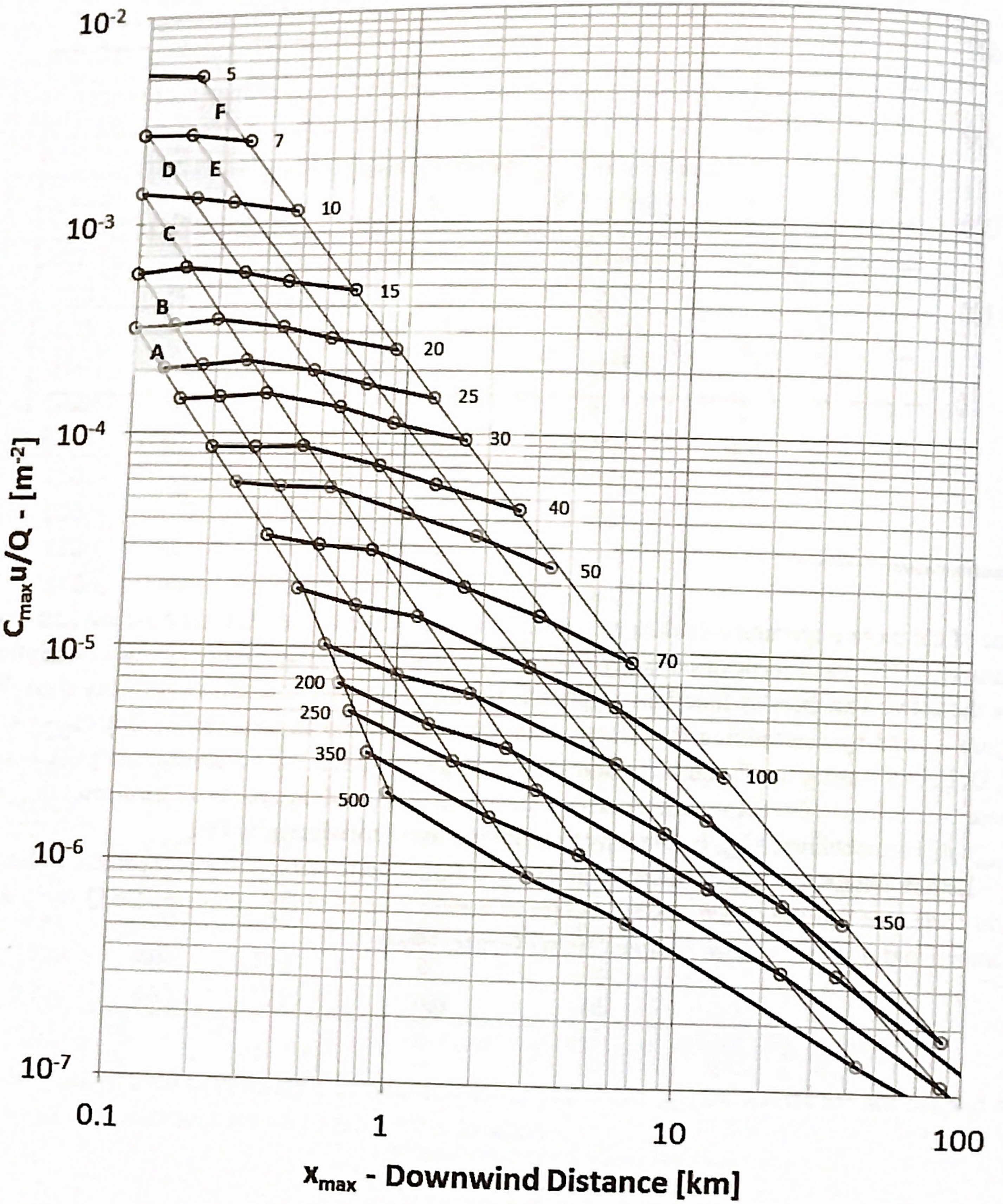
FIGURE 6-6. SO_x Concentration Contour Plot for Example 6-5. Distances are in meters. The concentration (in μg/m³) contours are not smooth in this plot due to the limited data and the simplified interpolation scheme used in generating the contours.



One of the more important calculations for this equation is finding the maximum ground level concentration (C_{max}) and its position (x_{max}). Figure 6-7 provides a graphical representation of solutions for these two variables as functions of effective stack height and atmospheric stability class. The figure is used by determining the effective stack height (H) and atmosphere stability class (A, B, C, D, E, or F) using the Pasquill classification scheme (section 5.7.2 – Stability Analysis). Locate these two points in the net superimposed on the log-log grid, and then the two coordinates (x_{max} and $C_{max}u_x/Q$) are obtained. C_{max} is found by multiplying the y-coordinate by Q/u_x.

Letters within the grid correspond to Pasquill atmospheric stability class. Numbers within the grid correspond to the effective stack height in meters. Use ½ of the calculated Cu/Q value if the contaminant does not reflect. Adapted from (Turner, 1994).

FIGURE 6-7. Value and Distance to Maximum Ground Level Concentration from an Elevated Source with Reflection (rural areas).



Example 6-6.

Find the position and value of the maximum downwind concentration for the data in Example 6-5.

Solution:

Use Figure 6-7 with the points H = 70 m and atmospheric stability class C. The x-coordinate yields xmax = 0.8 km or 800 m. The y-coordinate yields $C_{max}\, u_x/Q = 3 \times 10^{-5}\ m^{-2}$.

$$C_{max} = \left(\frac{C_{max} u_x}{Q}\right)\frac{Q}{u_x} = 3x10^{-5}\frac{1}{m^2}\left(\frac{125x10^6 \frac{\mu g}{s}}{6.1\frac{m}{s}}\right) = 615\frac{\mu g}{m^3}$$

Compare to Figure 6-6 where the distance to the maximum concentration is around 800 m, and has a value around 580 µg/m³, which is well within the implied accuracy of 25%.

6.4.5 Case 5. Line Source

A line source emission models pollutants from sources such as a long road with heavy traffic, or a series of sources along a river or harbor. Downwind concentrations are given by combining equations 6.3, 6.5, and 6.7. Assume the wind (u_x) is perpendicular to the road, the road runs in the y-direction. The F_y term is set to 1.0 because the line source distributes the emissions equally along its length, so there is no net dispersion in this direction. The units on the source, Q, become mass per unit length per unit time.

$$C(x,z) = \frac{2Q}{(2\pi)^{1/2} u_x \sigma_z} \exp\left(-\frac{z^2}{2\sigma_z^2}\right) \tag{6.14}$$

The z term can be modified to (z-H) for elevated sources.

Example 6-7.

Determine the concentration of CO 300 m downwind of a busy highway. The highway carries 3200 cars/hour at an average speed of 45 miles/hour. A 4 m/s wind perpendicular to the road. The atmospheric stability is class B. Note that Light Duty Gasoline Vehicles (passenger cars) have an average emission factor of 3.8 g CO/mile.

Solution:

Calculate Q from the emission factor and road use data. Note that for a line source the units of Q are [mass/(length·time)]. Determine σ_z from Figure 6-3. Finally, apply the given information to equation 6.14 for ground level (z=0):

$$Q = 3.8\frac{gCO}{Car \cdot mile}\frac{mile}{1600m}3200\frac{Car}{hour}\frac{hour}{3600\,\text{sec}} = 0.0021\frac{gCO}{m \cdot \text{sec}}$$

$$C(300,0) = \frac{2\left(0.0021\frac{gCO}{m \cdot \text{sec}}\right)}{(2\pi)^{1/2}\left(4\frac{m}{\text{sec}}\right)30m} = 14\frac{\mu g}{m^3}$$

This model assumes an infinitely long line source (road). Corrections can be applied at finite lengths to account for the edge effects (turns or other changes in direction). Interested readers may want to investigate the US-EPA website for air dispersion models at 'http://www.epa.gov/scram001/dispersion_alt.htm'.

6.4.6 *Case 6. Puff source*

A puff source is an emission where the material is released over a very short time, such as the spill of a volatile liquid, filling a tank, or during an explosion. Model these conditions as instantaneous releases from the location (0,0,0). The model equation is:

6.15 $$C(x,y,z) = \frac{2Q}{(2\pi)^{3/2}\sigma_x\sigma_y\sigma_z}\exp\left(-\frac{(x-u_x t)^2}{2\sigma_x^2}\right)\exp\left(-\frac{y^2}{2\sigma_y^2}\right)\exp\left(-\frac{z^2}{2\sigma_z^2}\right)$$

Note that this equation includes a σ_x term, representing the mixing length in the x-direction. It has a value the same as σ_y. Q in this equation is the total amount released and has units of mass. The maximum concentration always occurs along the downwind centerline at a position of x = ut. The concentration observed downwind will suddenly rise, and then quickly decrease as the puff passes a location. The last term becomes $[F_{z1} + F_{z2}]/2$ from equation 6.7 for the case of an elevated puff source with reflection.

The short times associated with an instantaneous release require modified mixing length calculations to reflect the differences from a continuous release. Table 6-3 lists the formulas to use for this situation (Slade, 1968).

Table 6-3. Mixing Length Formulas for Instantaneous Releases.

Mixing Length [m]	Atmospheric Stability	Formula
σ_x, σ_y	Unstable	$0.14(x)^{0.92}$
	Neutral	$0.06(x)^{0.92}$
	Very Stable	$0.02(x)^{0.89}$
σ_z	Unstable	$0.53(x)^{0.73}$
	Neutral	$0.15(x)^{0.70}$
	Very Stable	$0.05(x)^{0.61}$

■ *Example 6-8.*

A spill during the filling of a tank releases 24 kg of butane. Determine the maximum downwind concentration at 500 m and the time at which this occurs under very stable conditions with 3 m/s wind speed. Assume the entire spill vaporizes instantaneously.

Solution:

The maximum concentration will occur at x = ut, y=0, and z=0. Calculate the unknowns at these coordinates using equation 6.15 and the mixing lengths from Table 6 3.

$$\sigma_x = \sigma_y = 0.02(500)^{0.89} = 5m$$

$$\sigma_z = 0.05(500)^{0.61} = 2.2m$$

$$t = \frac{x}{u_x} = \frac{500m}{3\frac{m}{s}} = 167\,\text{sec} = 2.8\,\text{min}$$

$$C(500,0,0) = \frac{2(24{,}000g)}{(2\pi)^{3/2}(5m)(5m)(2.2m)} = 55.4\frac{g}{m^3}$$

The explosive limits of butane in air are LEL = 1.8% (lower explosive limit) and UEL = 8.4% (upper explosive limit). Air has a density of 1,200 g/m^3 at 1 atm and 20 °C. The fraction of butane at 500 m would constitute 55.4 / 1,200 *100% = 4.6%. This value is between the lower and upper explosive limits. The emission would certainly explode if any ignition source is in the area.

■ *Example 6-9.*

Plot the concentration-time profile at 300m, 450 m, 600 m in the downwind direction for the data in Example 6-8.

Solution:

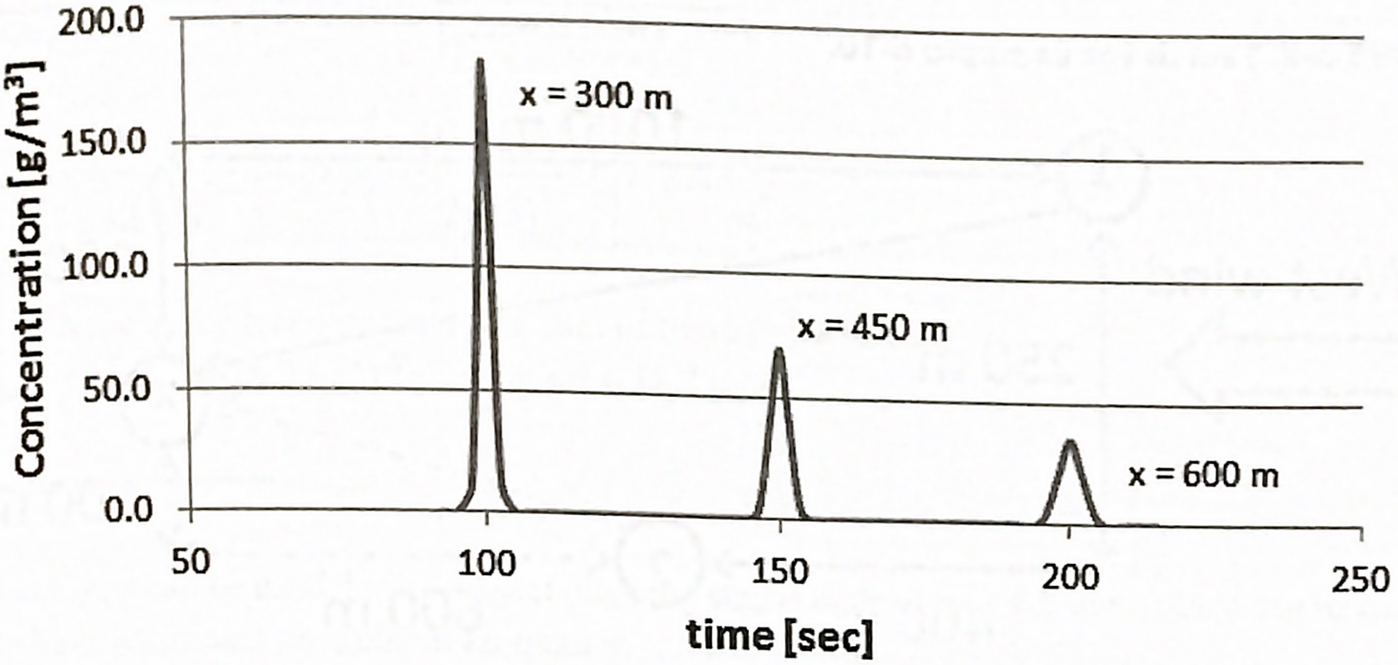
These calculations are similar to that shown in the previous example. A spreadsheet is useful to handle the repetitive calculations and to create the plot.

Table 6-4. Example 6-9 Calculations for Instantaneous Release of Butane.

Q	24000 g
u_x	3 m/s

x	σ_x	σ_y	σ_z	t	C(g/m^3)
300	3.2	3.2	1.6	92.5	0.0
300	3.2	3.2	1.6	97.5	11.8
300	3.2	3.2	1.6	99.0	118.1
300	3.2	3.2	1.6	100.0	183.1
300	3.2	3.2	1.6	101.0	118.1
300	3.2	3.2	1.6	102.5	11.8
300	3.2	3.2	1.6	107.5	0.0
450	4.6	4.6	2.1	138.8	0.0
450	4.6	4.6	2.1	146.3	3.5
450	4.6	4.6	2.1	148.5	43.0
450	4.6	4.6	2.1	150.0	69.5
450	4.6	4.6	2.1	151.5	43.0
450	4.6	4.6	2.1	153.8	3.5
450	4.6	4.6	2.1	161.3	0.0
600	5.9	5.9	2.5	185.0	0.0
600	5.9	5.9	2.5	195.0	1.4
600	5.9	5.9	2.5	198.0	21.0
600	5.9	5.9	2.5	200.0	34.9
600	5.9	5.9	2.5	202.0	21.0
600	5.9	5.9	2.5	205.0	1.4
600	5.9	5.9	2.5	215.0	0.0

FIGURE 6-8. Concentration Profile at Three Downwind Positions from an Instantaneous Puff Release.



The three peaks represent the concentration profiles at different distances and times.

6.4.7 Case 7. Multiple sources

Multiple source problems can become very complex, especially if the various plumes interact. A simplified approach is to assume superposition between the plumes such that the downwind concentration at any given location is the simple sum of all sources. The exact locations of the sources must be known. These solutions are also dependent on the wind direction, which could cause increases or decreases at a location depending on the source geometry.

■ ***Example 6-10.***

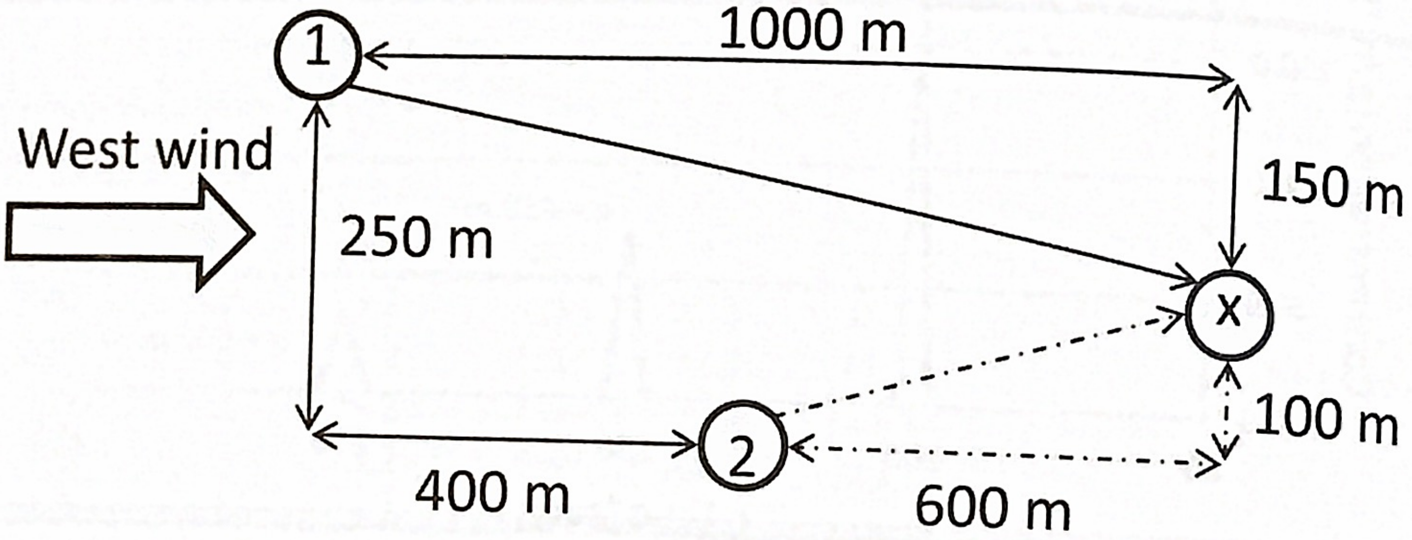
Two sources of NO_x emissions are located close together. Source one emits 220 g/s at an effective stack height of 48 m. Source two emits 55 g/s at an effective height of 38 m. Source two is located 250 m south and 400 m east of source one. Determine the ground level NO_x concentration at a receptor site located 1 km downwind and 150 m south of source one. The wind moves from the west at a speed of 2.5 m/s, measured at 10m. The atmospheric stability class is E.

Solution:

The concentration at the receptor site is obtained by summing the contributions at this location from each of the two sources. Equation 6.13 – Ground Level Concentrations from Elevated Source with

Reflection is used to determine the concentration from each source. A sketch of the locations of the two sources and the receptor site is useful in determining the coordinates for each calculation.

FIGURE 6-9. Sketch for Example 6-10.



The contribution from source one is $C_1(+1000,-150,0)$. The contribution from source two is $C_2(+600,+100,0)$. The calculation of these concentrations follows:

Source 1

$\sigma_y = 50m$

$\sigma_z = 21m$

$u_{48} = 2.5(48/10)^{0.35} = 4.3m/s$

$$C_1(1000,-200,0) = \frac{220x10^6 \frac{\mu g}{s}}{2\pi\left(4.3\frac{m}{s}\right)(50m)(13m)}\exp\left(-\frac{(-150)^2}{2(50)^2}\right)$$

$$\left[\exp\left(-\frac{(0-48)^2}{2(21)^2}\right)+\exp\left(-\frac{(0+48)^2}{2(21)^2}\right)\right] = 16.3\frac{\mu g}{m^3}$$

Source 2

$\sigma_y = 32m$

$\sigma_z = 13m$

$u_{38} = 2.5(38/10)^{0.35} = 4.0m/s$

$$C_2(600{,}100{,}0) = \frac{55x10^6\,\frac{\mu g}{s}}{2\pi\left(4.0\frac{m}{s}\right)(32m)(13m)}\exp\left(-\frac{(100)^2}{2(32)^2}\right)$$

$$\left[\exp\left(-\frac{(0-38)^2}{2(13)^2}\right)+\exp\left(-\frac{(0+38)^2}{2(13)^2}\right)\right] = 2.4\frac{\mu g}{m^3}$$

The increase at the receptor site is the sum of these two sources:

$C_{receptor} = C_1 + C_2 = 16.3\ \mu g/m^3 + 2.4\ \mu g/m^3 = 18.7\ \mu g/m^3$

The analysis can be used during project planning stages to determine if a new source can be expected to have an impact on ambient air quality.

6.5 Effect of Averaging Time

The estimates of horizontal and vertical mixing lengths are calculated from concentration measurements averaged over 10-minute intervals (Turner, 1994). These values for mixing length overestimate the concentrations at longer time intervals, and under-estimate at shorter time intervals. The determination of concentrations at different averaging times requires the value to be rescaled. One rescaling equation is given as (Nonhebel, 1960):

6.16 $$C_2 = C_1\left[\frac{t_1}{t_2}\right]^{0.17}$$

Where: C_x = the concentration at a given averaging time, and

t_x = averaging time in minutes

The models used and approved by the US-EPA assume the results from the above mixing length correlations are for 1-hour time-averaged concentrations not the 10-minute averages from the mixing length correlations. Thus, the US-EPA models predict conservative estimates of dispersion and associated concentrations.

■ *Example 6 -11.*

Determine the one-hour averaged PM^{10} concentration that would not exceed the US-EPA NAAQS.

Solution.

The NAAQS for PM10 is 150 μg/m³ averaged over 24 hours. Use equation 6.16 to determine the one-hour average:

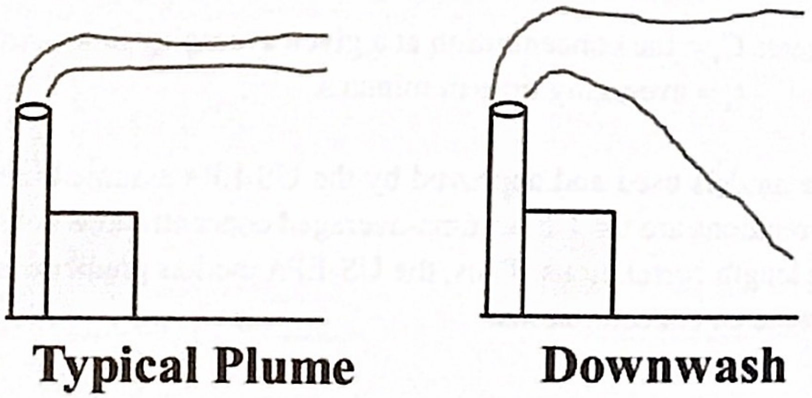
$$C_1 = C_{24}\left[\frac{24}{1}\right]^{0.17} = \left(150\frac{\mu g}{m^3}\right)(1.716) = 257\frac{\mu g}{m^3}$$

6.6 Effective Stack Height and Plume Rise

The most effective stacks are those which provide sufficient lift to the emissions to prevent them from interacting with ground level until they are dispersed and diluted to the point that they have little impact on ground level concentrations.

The main function of the stack is to launch the emissions far above ground level. It does not decrease the amount of emissions, but does allow the emissions to dilute within the atmosphere. The two mechanisms used to launch the plume are buoyancy and momentum. Heated emissions are less dense than the surrounding air, causing it to be buoyant. The heat originates within the process which generated the emissions (i.e. fuel combustion). The need for buoyancy limits the amount of heat recovery available from the emission stream. The speed of the gas exiting the stack provides it with vertical momentum. The exit velocity is determined from the volumetric flow of emissions and the diameter of the stack top. The diameter is chosen to give an exit velocity of at least 1.5 times the maximum expected wind speed at the stack height. Slower exit velocities may lead to stack tip downwash (see section 6.6.4), which causes the emissions to move downward behind the stack leading to elevated ground level pollution concentrations near the source, see Figure 6-10.

FIGURE 6-10. Example of normal plume and a plume experiencing downwash.



The effective stack height, H, is the sum of the physical stack height (h) and the plume rise (Δh):

6.17
$$H = h + \Delta h$$

Figure 6-1 shows an example of these terms. The stack height should be 2.5 times higher than the tallest nearby buildings. Airflow becomes turbulent as it moves over and around buildings, leading to enhanced mixing up to twice the height of the building. If the plume were to enter one of these turbulent zones it could mix with it, causing elevated pollution concentrations within the turbulent and wake zones.

There are many empirical formulae and theoretical models that can be used to determine the plume rise. These calculations use specific cases of meteorological and stack conditions. Differences in calculated values of plume rise may be as large as 10-fold (Briggs, 1975).

6.6.1 Holland Formula

One model that was once recommended by the US-EPA is the Holland formula (Holland, 1953):

6.18
$$\Delta h = \frac{v_s D_s}{u}\left[1.5 + 2.68x10^{-3}\left(\frac{T_s - T_a}{T_a}\right)P_a D_s\right]$$

Where: v_s = vertical stack gas velocity [m/s],
D_s = stack inside diameter at exit [m],
u = wind speed at stack height [m/s],
T_s = stack gas temperature [K],
T_a = ambient atmospheric temperature [K],
P_a = ambient atmospheric pressure [mbar],

This formula was developed for neutral atmospheric stability conditions. Holland suggested a correcting multiplier of 1.2 for Class A, 1.1 for B, 0.9 for E, and 0.8 for F.

6.6.2 Concawe Formula

Another model is the modified Concawe formula (Thomas, et al., 1970) which assumes that the plume rise is driven by buoyancy effects. It is calculated as:

6.19
$$\Delta h = \frac{4.71\left[mc_p\left(T_s - T_a\right)\right]^{0.444}}{u^{0.694}}$$

Where: m = flow rate of exit gas [kmol/s]
c_p = specific heat of exit gas [kJ/kmol/K]

The mass flow rate in equation 6.19 can be determined from the area of the stack exit, the exit velocity, and the ideal gas law for converting volume to mass:

$$m = \left(\frac{\pi}{4} D_s^2\right) v_s \left(\frac{P}{RT}\right) \quad (6.20)$$

6.6.3 Briggs Model

The current US-EPA method is the Briggs model, as used in the Industrial Source Complex (ICS3) dispersion models (US-EPA, 1995). This model determines plume rise by accounting for buoyancy and momentum driven plumes in stable and unstable or neutral conditions. In each situation, the plume rise is not instantaneous, rather it develops over time. This time is converted to distance using the wind speed. For each case a calculation will be presented of the horizontal distance the plume travels before it reaches its effective height and of the plume rise.

6.6.3.1 Unstable or Neutral Conditions

Plume rise predictions depend on whether the plume is dominated by buoyancy or momentum. A determination of which term is dominant is needed when the stack gas temperature, Ts, is greater than or equal to the ambient air temperature, Ta. The buoyancy flux parameter [m⁴/s³] is:

$$F_b = g v_s D_s^2 \left[\frac{T_s - T_a}{4T_s}\right] \quad (6.21)$$

Where: g = gravity [9.81 m/s²]

The momentum flux parameter [m⁴/s²] is:

$$F_m = v_s^2 D_s^2 \left[\frac{T_a}{4T_s}\right] \quad (6.22)$$

The determination is made by calculating a crossover temperature (ΔT_c) and comparing it to the temperature difference between the stack gas and the ambient air. The calculation depends on the value of the buoyancy flux:

$$\begin{aligned} &\Delta T_c = 0.297 \cdot T_s \frac{v_s^{1/3}}{D_s^{2/3}} \quad F_b < 55\frac{m^4}{s^3}\text{; and unstable or neutral conditions} \\ &\Delta T_c = 0.00575 \cdot T_s \frac{v_s^{2/3}}{D_s^{1/3}} \quad F_b \geq 55\frac{m^4}{s^3}\text{; and unstable or neutral conditions} \end{aligned} \quad (6.23)$$

The comparison between the actual temperature difference and the crossover temperature determines if the plume rise is buoyancy or momentum driven:

6.24

$$\begin{aligned}(T_s - T_a) &= \Delta T \geq \Delta T_c && \text{Buoyancy dominated plume rise}\\ (T_s - T_a) &= \Delta T < \Delta T_c && \text{Momentum dominated plume rise}\end{aligned}$$

6.6.3.1.1 *Unstable or Neutral Conditions - Buoyancy Dominant*

The calculations for the plume rise and horizontal distance to final rise are:

6.25

$$x_f = 49F_b^{5/8} \qquad \mathrm{F}_b < 55$$

$$\Delta h = 21.425\frac{F_b^{3/4}}{u}$$

or

6.26

$$x_f = 119F_b^{2/5} \qquad \mathrm{F}_b \geq 55$$

$$\Delta h = 38.71\frac{F_b^{3/5}}{u}$$

6.6.3.1.2 *Unstable or Neutral - Momentum Dominant*

Use the following calculations for the momentum dominated case as described above, or for cases where the stack temperature, Ts, is less than the ambient temperature, Ta:

6.27

$$x_f = 4D_s\frac{(v_s + 3u)^2}{v_s u} \qquad \text{for } \mathrm{F}_b \leq 0$$

$$x_f = 49F_b^{5/8} \qquad \text{for } 0 < \mathrm{F}_b \leq 55\frac{m^4}{s^3}$$

$$x_f = 119F_b^{2/5} \qquad \text{for } \mathrm{F}_b > 55\frac{m^4}{s^3}$$

6.28

$$\Delta h = 3D_s\frac{v_s}{u} \qquad \text{All } \mathrm{F}_b$$

(Briggs, 1969) suggests this equation fits best when $v_s/u > 4$.

6.6.3.2 *Stable Conditions*

For stable conditions (Class E or F) the relationships use a stability parameter, S [s^{-2}], given as

6.29

$$S = \frac{g}{T_a}\left(\frac{\Delta T}{\Delta h}\right)$$

Where: $\left(\frac{\Delta T}{\Delta h}\right)$ = Potential Temperature Gradient [K/m],
g = gravity (9.81 m/s2), and
Ta = ambient temperature.

If data are not available, the average potential temperature gradient is used; 0.02 K/m for class E, and 0.035 K/m for class F. The crossover temperature is:

6.30 $$\Delta T_c = 0.019582 \cdot T_s v_s S^{1/2}$$

The determination for buoyancy or momentum dominated plume rise is the same as given in equation 6.24.

6.6.3.2.1 Stable Conditions- Buoyancy Dominant

The plume characteristics are:

6.31
$$x_f = 2.0715 \frac{u}{S^{1/2}}$$

$$\Delta h = 2.6 \left(\frac{F_b}{uS}\right)^{1/3} \quad \text{for } u \geq 1.5 \text{ m/s}$$

$$\Delta h = 5 F_b^{1/4} S^{-3/8} \quad \text{for } u < 1.5 \text{ m/s}$$

6.6.3.2.2 Stable Conditions- Momentum Dominant

The plume characteristics are:

6.32
$$x_f = 0.5 \left(\frac{u}{S^{1/2}}\right)$$

$$\Delta h = 1.5 \left(\frac{F_m}{uS^{1/2}}\right)^{1/3}$$

Compare this value with the unstable-neutral momentum dominant plume rise, equation 6.28, and use the smaller of the two, because the plume rise in stable air should never exceed that in unstable or neutral conditions.

There is no single best correlation, and the predictions may vary by more than 50%. The choice depends on the specific local conditions and the assumptions used in generating the formula and model equations. As such the accuracy is limited.

Example 6-12.

Calculate the plume rise and the distance to maximum plume rise, using the Holland, modified Concawe, and Briggs models to make the estimates. The mass flow rate is 2.5 kmol/s with an average heat capacity of 35 kJ/kmol/K. The stack exit temperature is 450K; the ambient pressure is 980 mb; and the atmospheric ambient temperature is 27°C (300K). The gas exit velocity is 35 m/s. The wind speed is 5 m/s at the stack height in an unstable atmosphere (class B). The stack inside diameter at the exit is 3m.

Solution:

Apply the known data to equations 6.18, 6.19, and perform the calculations for each model.

Holland Formula:

$$\Delta h = \frac{\left(35\frac{m}{s}\right)(3m)}{\left(5\frac{m}{s}\right)}\left[1.5 + 2.68x10^{-3}\left(\frac{450-300}{300}\right)(980mbar)(3m)\right] = 114.2m$$

Modified Concawe Formula:

$$\Delta h = \frac{4.71\left[\left(2.5\frac{kmol}{s}\right)\left(35\frac{kJ}{kmol\cdot K}\right)(450-300)K\right]^{0.444}}{\left(5\frac{m}{s}\right)^{0.694}} = 103.8m$$

Briggs Model:

$$F_b = \left(9.81\frac{m}{s^2}\right)\left(35\frac{m}{s}\right)(3m)^2\left[\frac{450-300}{4(450)}\right] = 257.5\frac{m^4}{s^3}$$

$$F_m = \left(35\left[\frac{m}{s}\right]\right)^2(3m)^2\left[\frac{300}{4(450)}\right] = 1837.5\frac{m^4}{s^2}$$

Use equation 6.23 with Fb>55

$$\Delta T_c = 0.297\cdot(450K)\frac{(35)^{1/3}}{(3)^{2/3}} = 210.2K$$

Comparing the critical temperature with the stack-air difference we obtain:

$(450 - 300) = 150 < 210$

Since the critical temperature is greater than the stack-ambient air temperature difference, the plume is momentum dominated. Finally, calculate the distance and plume rise from equations 6.27 and 6.28 for unstable or neutral, momentum dominated conditions:

$$x_f = 119(257.5)^{2/5} = 1{,}100 \text{ m}$$

$$\Delta h = 3(3m)\frac{\left(35\frac{m}{s}\right)}{\left(5\frac{m}{s}\right)} = 63\text{m}$$

The large differences in values are normal. In this case, the Briggs model is probably better as the other two models always assume buoyancy dominated plume rise, yet the critical temperature showed the system is momentum dominated.

6.6.4 Stack Tip Downwash

Downwash can occur when the exit velocity is less than 1.5 times the wind speed. As the wind moves past a structure, it can create a turbulent wake zone on the downwind side. The wake causes recirculating eddies and regions of very high vertical mixing. The turbulent zone can extend twice the building height and extend five to ten times the height downwind. (Briggs, 1974) suggested that downwash be modeled as a reduction to the physical height of the stack. One model equation is:

6.33 $$H = h + 2D_s\left[\frac{v_s}{u} - 1.5\right] \quad v_s < 1.5u$$

Where: h = physical stack height [m],

D_s = inside diameter of stack at exit [m],

v_s = vertical velocity of gas at stack exit [m/s], and

u = wind speed at stack height h [m/s].

This equation yields an effective height, H, which is less than h.

In addition to designing high exit velocity, the stack itself can be designed to reduce the size and magnitude of the wake caused by the stack. Two design devices to accomplish this are a large flat disk located circumferentially at the stack exit with a diameter of 3 times the stack exit diameter, and helical wind turning vanes located around the stack (Cooper, et al., 2011).

6.7 Other Air Dispersion Models

The US EPA maintains an air dispersion modeling database (US-EPA, 2010). It is a model clearinghouse that contains screening and refined models for use in developing air permits. The site provides guidance in the use of these models and alternative models. Most of the models include computer code (typically written in the FORTRAN language) for running or compiling the model. User guides accompany each to help understand the input and output for each model. Specialized models include photochemical effects, multi-pollutant applications, receptor analysis, meteorological concerns, and permit guidance.

6.8 Long Range Transport (>50 km)

The Gaussian model is adequate for estimating pollutant concentrations up to approximately 50 km from the source. Beyond this limit, large-scale weather systems, variations in sunlight, and the presence of precipitation have larger effects on the plume. Most pollutants have atmospheric lifetimes that exceed the time needed to move 50km. A different type of model is used at these greater distances to account for the greater variety of conditions a plume encounters. These methods for studying atmospheric transport over long distances use Lagrangian models of fluid flow (Lin, et al., 2011). The models work by simulating atmospheric flow of air and following the motions of parcels, or particles, embedded in the atmospheric flow. Lagrangian models track the movement of the parcels using a moving frame of reference. The movement of the parcel tends toward the average flow of the fluid, but diverts from this average flow field due to turbulence, washout, chemical reactions, or other changes in the parcels environment. The atmospheric flow field is determined from meteorological observations and fluid flow models. The models are used to track intercontinental transport of pollutant plumes or radioactive releases. Running the models backward in time, using historical meteorological data, can help determine the source regions of observed contaminants.

One long-range transport model developed by the US-NOAA and Australia's Bureau of Meteorology is called HYbrid Single-Particle Lagrangian Integrated Trajectory or HYSPLIT (US-NOAA, 2011). It is a modeling system that computes air parcel trajectories that include complex dispersion, deposition, advanced advection algorithms, meteorological stabilities, and chemical transformations. The model is based on either puff or particle dispersion. In the puff model, puffs expand until they exceed the size of the meteorological cell (vertical or horizontal). Then they split into several new puffs, each with its share of the pollutant mass. In particle mode, a fixed number of particles are advected through the model domain by the mean wind velocity field and spread by a turbulent mixing component. Another model, called FLEXTRA/ FLEXPART, (Stohl, 2001) is a kinematic trajectory model used to calculate several types of trajectories such as 3D, isentropic, isobaric, and boundary layer trajectories. It is developed by the Institute of Meteorology and Geophysics in Vienna by Andreas Stohl, Gerhard Wotawa, and Petra Seibert.

6.9 Questions

* - Questions and problems may require additional information not included in the textbook.

1. Why are screening level models based on estimations that are very conservative. That is why is it acceptable that they always predict higher concentrations than are observed?
2. The x-direction mixing was ignored in the derivation of equation 6.2. Explain how and comment on the effect this assumptions would have on the actual concentrations.
3. Describe the effect on ground level concentrations if wind speed (ux) was allowed to vary in the z-direction around an elevated source (see equation 5.12).
4. Suggest an addition to the Gaussian model that would account for the reduction in concentration of a pollutant that reacts in the atmosphere.
5. Sketch a concentration contour of a long plume that is suddenly exposed to a wind direction shift of 90°. How would this differ from a line source?
6. Sketch the elevation view of a plume from an elevated source that undergoes reflection from the ground and an inversion layer located at an elevation of L. Identify the sources of the terms given in equation 6.7.
7. Why are Gaussian screening models only useful up to 50 km? Would it be possible to improve the long-range predictions by adding an additional term to the Gaussian model?
8. What would be the effect on ground level concentrations if plume rise were ignored?
9. How could the Gaussian model be altered to model a contaminant that only partially reflects?
10. Visit the US-EPA technology transfer network website. Find the names of 3 alternative screening level models (not ISC3) for predicting dispersion.* [http://www.epa.gov/scram001/dispersion_screening.htm]
11. Make a list of three questions you have about this chapter or air pollution concerns you have.

6.10 Problems

1. Consider the following cases. Would they need to model their air emissions. Assume that each case is located in a class II region that is currently in attainment, with no nearby class I regions.
   a) A new coal fired boiler, burning 0.5 tons/hr of coal with an 8% ash content. Assume the only emission is PM.
   b) A power generator burns 5000 gal/ hr of No. 2 fuel oil in an existing facility, and undergoes an expansion that doubles its use of fuel oil. Assume the only emission is PM.
   c) A new coal fired boiler which burns 20 ton/hr of bituminous coal with 3% sulfur, and with equipment that will remove 80% of SO_x. Assume SO_x is the only emission.
   d) A medical waste incinerator burns 1 ton/hr and removes 97% of the PM generated. Assume the only emission is PM.

2. Determine the y-direction mixing length, σ_y, at 2 km for each atmospheric stability class in rural and urban areas.

3. Determine the z-direction mixing length, σ_z, at 2 km for each atmospheric stability class in rural and urban areas.

4. Determine the downwind concentration [$\mu g/m^3$] of PM 800 m from a rural ground level source if the emission rate is 30.0 g/s. The midday weather is sunny with a gentle breeze.

5. Determine the emission rate of SO_x [kg/hr] from an urban ground level source if the 1,000 m downwind concentration is 5.0 $\mu g/m^3$. The evening weather is overcast with a light breeze.

6. Determine the 1-km downwind ground level concentration of PM [$\mu g/m^3$] from an urban power plant that burns 3 ton/hr of bituminous coal containing 5.5% ash, and having 99% PM removal. The source emits from a stack with effective height 100m. The wind at the stack height is 6 m/s and the atmospheric stability is class C.

7. Determine the effective stack height needed to reduce a rural emission of 1.5 g/s of PM to an ambient ground level concentration of 5 μg/m3 at a rural location 700 m downwind. The wind is 3.2 m/s at 10 m elevation, in class D conditions.

8. Calculate the 1 km downwind rural concentration at (a) stack height and (b) ground level of 20 μm particulates (ϱ=1.5g/cm^3) emitted at a rate of 2.2 g/s from a stack with an effective height of 50 m. The wind speed at stack height is 5 m/s in class D conditions. Hint: These are large particulates and they may settle more quickly than a gas phase emission.

9. Consider a Hawaiian rural sugar mill that consumes 100 ton/hr of sugar cane. The cane contains about 15 wt% sucrose solution. The remaining plant matter is a waste called bagasse, which can be burned to generate steam. This mill collects 90% of the PM generated from the process. The remaining PM and other waste gasses (2.5 kmol/s) are discharged at 340 K, have a heat capacity of 30 kJ/ kmol/ K, and are emitted from a 25 m stack. The local weather is 305 K on a day with slightly unstable air and a wind speed of 4 m/s measured at a height of 10 m.
   a) Calculate the PM emission rate [g/s],
   b) Determine the effective stack height using the modified Concawe formula,
   c) Plot the ground level downwind concentrations for $0 < x < 5000$ m,
   d) Find the maximum downwind ground level concentration and its position,
   e) Draw a ground level isopleth map with $-500 \text{ m} < y < 500$ m and x as in part c.

10. Determine the effective height of a stack needed to keep the maximum ground level ambient air concentration below 10 μg/m^3 from a source that emits 12 g/s of NO_x in a rural area with wind speed 4 m/s measured at the stack height and moderately stable air.

11. The critical wind speed is the wind speed that yields the largest value of C_{max}. Note that the downwind concentration is inversely proportional to wind speed, which will decrease the concentration as wind speed increases. The effective stack height is also inversely proportional to wind speed, but this will tend to increase the concentration as wind speed increases. Since the two terms are in opposition, the concentration will go through a maximum with increasing wind speed. Determine this critical speed and concentration for a 85 g/s emission of SO_x from a stack of 40 m physical height, under atmospheric stability class D in an rural area. Use the modified Concawe formula with the term $[mcp(Ts\text{-}Ta)] = 14{,}000$ kJ/s. Hint: Figure 6-7 will greatly reduce the calculations.

12. Determine the effect of atmospheric stability class on the ground level concentration of CO at a location 500 m downwind from a busy urban highway for a 3 m/s cross wind perpendicular to the road. Assume the traffic emits 0.003 g/m/sec of PM.

13. An explosion releases 5 kg of dust instantaneously into the air at ground level. The atmospheric conditions are unstable with a 4.5 m/s wind. Estimate the maximum concentration 1 km down wind. How long after the release will this maximum occur?

14. Prepare an isopleth map [C(x,y,0)] of the release in the problem13 above at t = 5 min, t = 10 min, and t = 15 min.

15. Consider the NO_x emissions from two rural sources. The second source is located 500 m south and 500 m east of the first source. Source 1 emits 20.5 g/s and has an effective height of 100 m.

Source 2 emits 35 g/s and has an effective height of 150 m. Sketch the locations of the stacks and the receptor site. Determine the concentration at a receptor located 4 km east and 200 m south of source one. Atmospheric conditions are neutral with a westerly wind of 5 m/s measured at 10 m.

16. Using the emission sources and data from problem 15, estimate the ground level concentration at a receptor location 4 km downwind of source one, assuming a NW wind at 5 m/s.

17. Using the emission sources and data from problem 15, estimate the ground level concentration at a receptor location 4 km downwind of source one, assuming a SW wind at 3 m/s.

18. Assume the result in Example 6-6 is a 10 minute averaged concentration. Would this concentration exceed the one hour SO_x standard in the US-EPA NAAQS?

19. Consider a 450K emission source that exits a 2 m diameter, 50 m high stack. The emissions leave at 20 m/s into a rural, neutral atmosphere with wind (at 10 m) of 5 m/s, 300 K, and 980 mbar. The heat capacity of the emission is 35 kJ/(kmol K). Determine the plume rise using a) Holland formula, b) modified Concawe formula, and c) Briggs method. Hint: R = 0.083145 (m^3 bar) / (kmol K).

20. Calculate the effective stack height for the data in problem 19, except let u at H be equal to v_s.

6.11 Group Project Ideas

For each project, the students should work in small groups and present their findings in either a short report (5-8 pages), a poster, or a 15 minute oral presentation.

1. Combine the information from the controlled emissions from a particular local emission source of your choice (such as your university power plant), a standard wind rose, a map of your location, and your own calculations of dispersion in each direction. Superimpose your ground level concentrations onto the map for each wind rose direction. How would you expect air quality to be impacted from the site? Be sure to weight your calculations by the wind rose percentages at each velocity and each direction. Emissions data is available from the source's website or EPA.gov/state environmental quality websites.

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