Re-formulation of Plume Spread for Near-Surface Dispersion

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ABSTRACT

Recent concerns about effects of automobile emissions on the health of people living close to roads have motivated an examination of models to estimate dispersion in the surface boundary layer. During the development of a new line source dispersion model, RLINE (Snyder et. al 2013), analysis of data from a tracer field study led to a re-examination of near-surface dispersion resulting in new formulations for horizontal and vertical plume spread presented in this paper. The equations for vertical spread use the solution of the two-dimensional diffusion equation, in which the eddy diffusivity, based on surface layer similarity, is a function of surface micrometeorological variables such as surface friction velocity and Monin-Obukhov length. The horizontal plume spread equations are based on Eckman's (1994) suggestion that plume spread is governed by horizontal turbulent velocity fluctuations and the vertical variation of the wind speed at mean plume height. Concentration estimates based on the proposed plume spread equations compare well with data from both the Prairie Grass experiment (Barad 1958) as well as the recently conducted Idaho Falls experiment (Finn at al. 2010). One of the major conclusions of this study is that the plume spreads as well as the wind speed used to estimate concentrations in a dispersion model form a set of coupled variables.

KEYWORDS

Plume spread, near surface dispersion, surface releases, similarity theory, model performance, Prairie Grass experiment, Idaho Falls experiment, RLINE

1 Introduction

New interest in modeling dispersion from surface releases has been sparked by recent studies showing that people living and working near roadways are exposed to elevated levels of pollution and are at increased risk of respiratory problems (e.g., Nitta et al. 1993; McConnell et al. 2006), birth and developmental defects (e.g., Wilhelm and Ritz 2003), premature mortality (e.g., Finkelstein et al. 2004; Jerrett et al. 2005), cardiovascular effects (e.g., Peters et al. 2004; Riediker et al. 2004), and cancer (e.g., Harrison et al. 1999; Pearson et al. 2000). The near roadway pollutants originate primarily from automobiles and trucks, which are near surface releases.

In response to this concern with the health effects, the USEPA initiated a program to examine the many factors that influence the dispersion of mobile source emissions and develop a line source model, RLINE (Snyder et. al. 2013), to model roadway impacts. The model development program included a tracer field study (Finn et al. 2010) in Idaho Falls to provide new data for examining near-surface dispersion from a line source. An analysis of the Idaho Falls data indicated that currently used dispersion curves (Briggs 1982; Venkatram 1992), based on the Prairie Grass field study (Barad 1958) do not provide a satisfactory description of both the new and historical data. This led to a reformulation of the plume spread equations, which is the primary topic of this paper.

2 Current Plume Spread Formulation and Evaluation

Vertical dispersion in the surface layer is well understood. The underlying theory has a long history (e.g. Chaudhry and Meroney 1973; Van Ulden 1978), and has been evaluated extensively with data from field studies and wind tunnel experiments. This theoretical understanding has been translated into formulations for plume spreads that are used in dispersion models such as AERMOD (Cimorelli et al. 2005). These formulations are functions of micrometeorological variables, such as surface friction velocity and Monin-Obukhov length, and have been evaluated with data from the Prairie Grass field study (Barad 1958). Examples are those proposed by Venkatram (1982) and Briggs (1982). A version of this equation is included in AERMOD (Cimorelli et al. 2005).

The equations for plume spread are evaluated within the framework of the Gaussian dispersion model for estimating the concentration at a receptor, *(x,y,z)*,

$$\frac{C(x,y,z)}{Q} = \frac{1}{2\pi\sigma_z\sigma_y U}\left(exp\left[-\frac{1}{2}\left(\frac{z-z_s}{\sigma_z}\right)^2\right] + exp\left[-\frac{1}{2}\left(\frac{z+z_s}{\sigma_z}\right)^2\right]\right)exp\left(-\frac{y^2}{2\sigma_y^2}\right), \quad (1)$$

where σ_y and σ_z are a measure of plume spread in the horizontal and vertical, respectively, Q is the emission rate, U is the near surface wind speed, and z_s is the source height.

In this paper, we adopt the plume spread equations incorporated in AERMOD (Cimorelli et al. 2005; Venkatram 1992) to be representative of formulations in current use. The vertical spread, σ_z, of a surface release is estimated from

$$\begin{aligned} \sigma_z &= \sqrt{\frac{2}{\pi}}\frac{u_* x}{U}\left(1+0.7\frac{x}{L}\right)^{-1/3} \quad L > 0.0 \\ &= \sqrt{\frac{2}{\pi}}\frac{u_* x}{U}\left(1+0.0006\left(\frac{x}{L}\right)^2\right)^{1/2} \quad L < 0.0 \end{aligned} \quad (2)$$

where L is the Monin-Obukhov length defined by $L = -T_0 u_*^3/(\kappa g Q_0)$, Q_0 is the surface kinematic heat flux, u_* is the surface friction velocity, g is the acceleration due to gravity, T_0 is a reference temperature, and κ is the von Karman constant taken to be 0.40.

The horizontal spread of the plume used in Equation (1) is a purely empirical equation that fits the data from Prairie Grass (Cimorelli et al. 2005):

$$\begin{aligned} &\sigma_y = \frac{\sigma_v x}{U}(1+78X)^{-0.3} \\ &\text{where } X = \frac{\sigma_v x}{U z_i} \end{aligned} \quad (3)$$

and σ_v is the standard deviation of the horizontal velocity fluctuations and z_i is the mixed layer height.

Under low wind speeds, horizontal meandering of the wind spreads the plume over large azimuth angles, which might lead to concentrations upwind relative to the vector averaged wind direction. We account for meandering by adopting the approach in AERMOD (Cimorelli et al. 2005) which assumes that when the mean wind speed is close to zero, the horizontal plume spread covers 360°. Then, the concentration is taken to be a weighted average of concentrations of two possible states: a random spread state, and a plume state. In the random spread state, the release is allowed to spread radially in all horizontal directions. Then, the horizontal distribution in Equation (1) is replaced by:

$$H(x_r, y_r) = f_r \frac{1}{2\pi r} + (1 - f_r)\frac{1}{\sqrt{2\pi}\sigma_y} exp\left(-\frac{y^2}{2\sigma_y^2}\right). \quad (4)$$

where the first term represents the random state in which the plume spread covers 2π radians, and r is the distance between the source and receptor. The second term is the plume state corresponding to the Gaussian distribution.

The plume is transported at an effective velocity given by

$$U_e = (\sigma_u^2 + \sigma_v^2 + U(\bar{z})^2)^{1/2} = (2\sigma_v^2 + U(\bar{z})^2)^{1/2}. \quad (5)$$

where $U(\bar{z})$ is the wind speed evaluated at the mean plume height and the expression assumes that $\sigma_v \approx \sigma_u$. The mean plume height, $\bar{z}$, a function of vertical spread, is formulated in section 3. Note that the effective velocity is non-zero even when the mean velocity is zero. The minimum value of the effective velocity, U_e, is $\sqrt{2}\sigma_v$.

The weight for the random component in Equation (4) is taken to be

$$f_r = \frac{2\sigma_v^2}{U_e^2}. \quad (6)$$

This ensures that the weight for the random component goes to unity when the mean wind approaches zero. The success of this meandering correction depends on measurements of σ_v, which presumably reflect meandering when the wind speed is close to zero. If measurements are not available, we have to estimate σ_v from other meteorological variables (see Cimorelli et al. 2005).

The need to specify an effective wind speed, U_e, in Equations (1) thru (6) highlights a problem with the application of the Gaussian dispersion equation to releases in the surface layer, where the wind speed varies rapidly with height. However, if the source height and the receptor height are close to zero, and the receptor is close to the line source, the ground-level concentration is insensitive to the choice of the height to evaluate the wind speed because the ground-level concentration is inversely proportional to the product $\sigma_z U$ (see Equation 2), which is independent of U. When the release and receptor heights are non-zero, the concentration becomes more sensitive to U. This point is discussed in detail in section 3.

We first examine the performance of current formulations for plume spread using data from the two field studies described next.

2.1 Evaluation with Prairie Grass Field Study

In each experiment of the Prairie Grass Project (Barad 1958) the tracer, SO_2, was released from a point location at a height of 0.46 m, for an interval of 10 min, and the concentration was sampled along five semi-circular arcs at distances of 50, 100, 200, 400, and 800 m from the release. The samplers on the arcs were spaced at 2° intervals on the first four arcs, and at 1° on the 800-m arc for a total of 545 sampler locations. Roughly half of the 70 experiments were conducted under stable conditions, which covered both low and high wind-speed conditions. The mean wind was measured at 8 levels ranging from 0.125 m to 16 m. The standard deviation of the horizontal wind direction and vertical velocity fluctuations used in this study were derived from bivane measurements at a height of 2 m. The micrometeorological inputs, u_* and L, computed by fitting M-O velocity and temperature profiles to tower measurements, are taken from van Ulden (1978). Lee and Irwin (1997) fitted Gaussian distributions to the concentrations along each arc and derived horizontal spreads and peak concentrations for each arc. These data were obtained from Arhus University, Denmark at http://envs.au.dk/en/knowledge/air/models/background/omlprairie/excelprairie/.

Model performance estimates of concentration are compared qualitatively to measurements with the use of scatter plots. In addition, model performance is quantified using the performance statistics as described in Venkatram (2008). The quantitative model performance measures used here are the geometric mean bias (m_g), the geometric standard deviation (s_g) and the fraction of estimates within a factor of two of the measured value (fac2). Venkatram's definition of m_g suggests that a model is over predictive when $m_g < 1$. We have flipped the ratio of observed-to-predicted concentrations here, so that $m_g > 1$ is indicative of a model over-prediction; $m_g < 1$ is indicative of a model under-prediction. To avoid the effect of outliers on the computation of these statistics, we use the following definitions of the geometric mean bias and standard deviation:

$$m_g = median\left(\frac{C_p}{C_o}\right) \tag{7}$$

and

$$s_g = exp\left(\frac{\ln(F)}{\sqrt{2}\, erf^{-1}(A_F)}\right), \tag{8}$$

where C is the concentration, either observed (subscript 'o') or predicted (subscript 'p'), F is taken to be 2, A_F is the fraction of the ratio, $C_p/(C_o m_g)$, between $1/F$ and F, and erf^{-1} is the inverse error function. Equation (26) is equivalent to fitting a lognormal distribution to the values of C_p/C_o between 0.5 and 2, so s_g equals one when 100% of the predictions lie within a factor of two interval. Only when values are outside of a factor of two interval is the value of s_g greater than one. Observed and predicted concentrations are paired in time and space.

Figure 1 shows the performance of Equations (2) and (3) applied within the RLINE framework, a line source model described in the companion paper (Snyder et al. 2013). While this model is based on numerically approximating a line with point sources, in this application we used the calculation of concentration from one point source. The model is generally unbiased in stable conditions and overestimates in unstable conditions. Although there is inevitable scatter, most of the model estimates are within a factor of two of the observations. The bottom panel of Figure 1 shows that the model has a tendency to overpredict the peak concentrations at all downwind distances for all conditions.

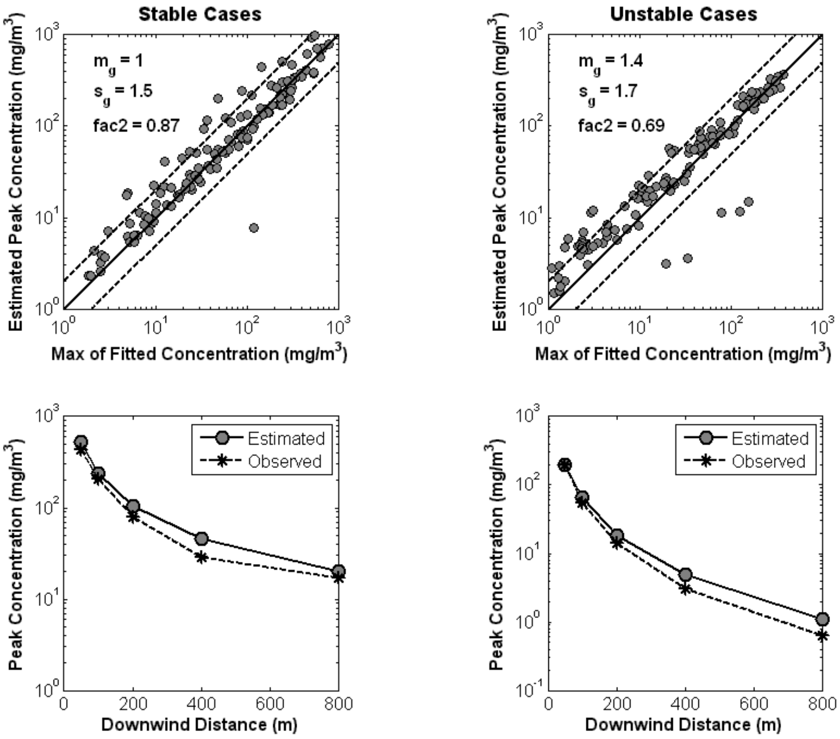

Figure 1: Comparison of concentration estimates from Equations (1-6) to observations at Prairie Grass. Bottom panel compares mean of the estimated peak concentrations at each downwind distance with corresponding observations.

The performance of Equation (3) in describing the horizontal spread is seen in Figure 2. The observed horizontal spreads were estimated by fitting a Gaussian distribution to the ground-level concentration at each radial distance from the source. The biases in σ_y contribute to the biases seen in the estimated concentrations presented in Figure 1.

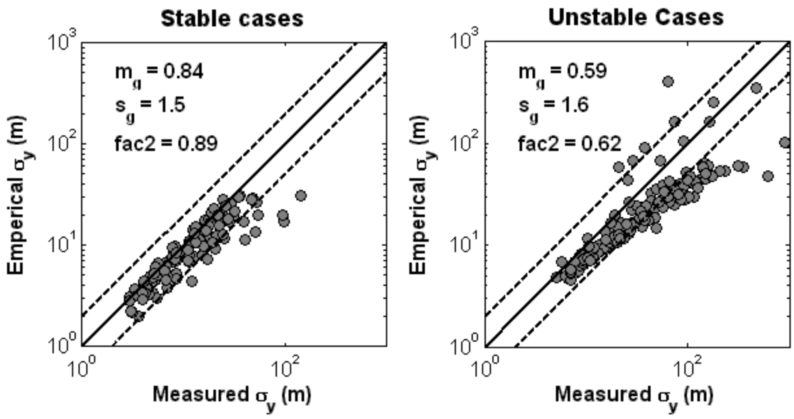

Figure 2: Comparison of σ_y estimates from Equations (3) with measured values at Prairie Grass. The solid line represents the one-to-one line, the parallel dashed lines represent factor of two intervals.

How do these dispersion formulations derived from Prairie Grass work for Idaho Falls? We briefly describe the Idaho Falls experiment before answering this question.

2.2 Evaluation with Idaho Falls Field Experiment

The field study was conducted in 2008 (Finn et al. 2010) near NOAA's Grid 3 diffusion grid at the Department of Energy's Idaho National Laboratory (INL). The Grid 3 area on the INL is located across a broad, relatively flat plain on the western edge of the Snake River Plain in southeast Idaho. The objective of the study was to examine the impact of roadway sound barriers on dispersion of emissions from a line source. The tracer, SF_6, was released simultaneously from two 54m line sources positioned one meter above ground level, representing pollutant source roadway. One of the releases was 6 m upwind (generally) of a 90 meter long and 6 meter high noise barrier while the other release was without a barrier. The tracer was sampled on identical grids of 58 samplers extending out to 180 m in the general downwind direction from the source. Two of the samplers were deployed upwind of the release line to check for possible upwind tracer dispersion. Bag samplers were positioned at 1.5 m AGL in a rectangular array from 18 to 180 meters downwind of the source line. The SF_6 tracer was simultaneously released from the line source for each grid beginning 15 min before the sampler measurements started to establish a quasi-steady state concentration field and continued until the end of each test. An array of six 3-d sonic anemometers was deployed for sensing winds and turbulence. Five tests were conducted during the study, each spanning a 3-h period broken into 15-min tracer sampling intervals. One test was conducted in unstable conditions, one in neutral conditions, and three in stable conditions. The micrometeological conditions corresponding to these test are shown in Table 1.

Table 1: Summary of the conditions during each day of the Idaho Falls 2008 field test.

Test Day	L (m)	u_* (m/s)	Reference Wind Speed (m/s)	Wind Direction (deg)
1 – Slightly Convective	-(500-181.8)	0.52-0.88	5.5-8.1	192.7-228.1
2 - Convective	-(29.8-1.7)	0.15-0.34	0.7-2.5	189-203.9
3 – Slightly Stable	+(35.3-62.0)	0.28-0.35	3.2-3.6	202-208.6

5 - Stable	+(4.9-17.3)	0.05-0.19	1.6-2.4	194.1-230.8

The sampler density was greatest near the sources and decreased in the downwind direction. A single tracer line source was used to simulate roadway emissions for the primary and control experimental grids.

Test 1 was conducted on October 9, 2008 from 1230-1530 hours Mountain Standard Time (MST) in neutral stability conditions. Winds were generally well in excess of 5 m s^{-1} and skies were heavily overcast. Test 2 was conducted on October 17, 2008 from 1300-1600 hours MST in unstable conditions. Skies were clear and sunny throughout the test period and winds were light from 1 to 3 m/s. Test 3 was conducted on October 18, 2008 from 1600-1900 hours MST in weakly stable conditions. The wind direction was very close to ideal until the last hour of the experiment when a transition in the wind field occurred. Skies were clear throughout the experiment. Test 4 was conducted in moderately to strongly stable conditions but was not used because the wind direction was unfavourable with respect to the source and sampler grid orientation. Test 5 was conducted on October 24, 2008 from 1800-2100 hours MST in moderate to strongly stable conditions.

Again we computed the concentrations associated with the finite line source using RLINE (Snyder et al. 2013) with the dispersion parameters of Equations (2) and (3). The surface roughness length, z_0, was found to be 0.053 m, which was obtained by fitting the Monin-Obukhov (MO) similarity profile to the wind speeds measured at the 3 m sonic anemometer level during a set of trials in which the wind direction was within 20 degrees from the normal to the line source.

Figure 3 shows the comparison between concentration estimates and concentrations made at the samplers in the Idaho Falls experiments. The model estimates and the observations correspond to the maximum at each downwind distance. Although there is a high degree of correlation between model estimates and observations, the concentrations are underestimated at low concentrations for the neutral and slightly stable cases. There is a slight tendency for the concentrations to be overestimated during the highly unstable conditions of Test 2. During the very stable conditions of Test 5, there are a number of concentration values that are underestimated by close to a factor of two.

Although most of the model estimates are within a factor of two of the observed values, it is clear from Figure 3 that the discrepancies show a trend with concentrations. The concentrations during stable and neutral conditions are substantially underestimated. These results motivated a reexamination of the plume dispersion equations, which we describe in the next section.

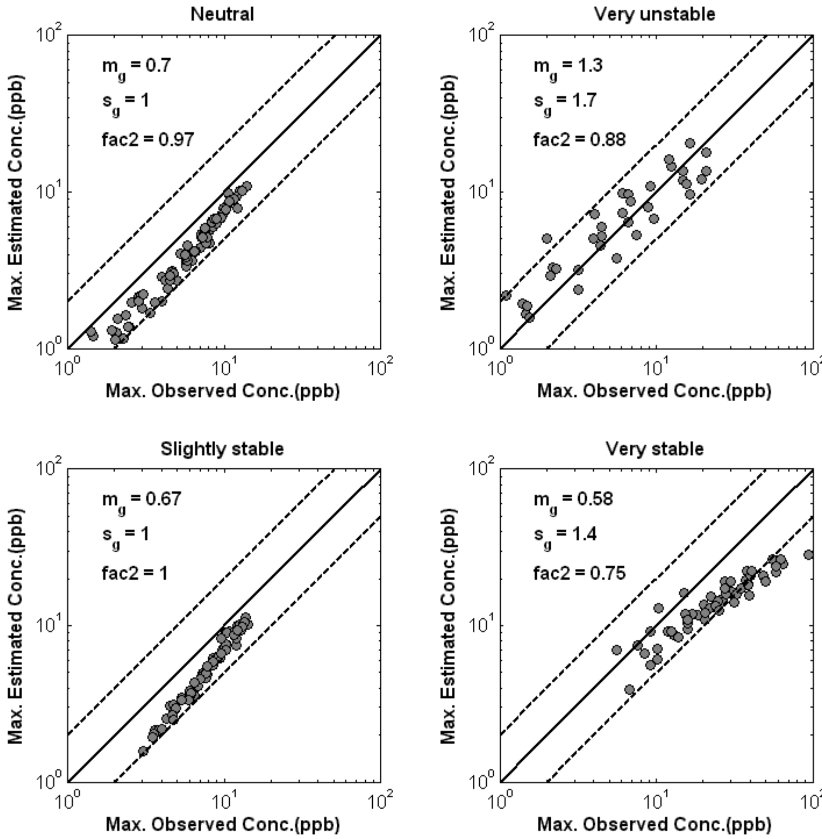

Figure 3: Comparison of maximum concentration estimates based on plume dispersion equations (1) to (3) with corresponding observations from Idaho Falls. The solid line represents the one-to-one line, the parallel dashed lines represent factor of two intervals.

3 Reformulated Plume Spreads and Evaluation

The starting point of the reformulation is the model proposed by van Ulden (1978) and evaluated with observations from the Prairie Grass experiment (Barad 1958). This model, which is similar to those developed by others (Chaudry and Meroney 1973), is based on the solution of the eddy diffusivity based mass conservation equation. This starting point, together with the observation that mean plume height and vertical spread are closely related parameters, suggests beginning with a derivation of the mean plume height and then relating that to vertical spread.

The crosswind integrated concentration associated with a point source at ground-level with strength Q, is taken to satisfy

$$U(z)\frac{\partial C}{\partial x} = \frac{\partial}{\partial z}\left(K(z)\frac{\partial C}{\partial z}\right) \tag{9}$$

If we assume that the wind speed, $U(z)$, and the eddy diffusivity $K(z)$ are described by power laws

$$U(z) = U_r\left(\frac{z}{z_r}\right)^p \tag{10}$$

and

$$K(z) = K_r\left(\frac{z}{z_r}\right)^n \tag{11}$$

where U_r and K_r are values at a reference height z_r, Equation (9) has the solution

$$\frac{C(x,z)}{Q} = \frac{A}{\bar{U}\bar{z}}\exp\left[\left(\frac{Bz}{\bar{z}}\right)^s\right] \tag{12}$$

where the mean plume velocity, $\bar{U}$, and mean plume height, $\bar{z}$, are defined by

$$\bar{U} = \frac{\int CU(z)dz}{\int Cdz} \text{ and } \bar{z} = \frac{\int Czdz}{\int Cdz}, \tag{13}$$

the constants in the solution are

$$B = \frac{\Gamma(2/s)}{\Gamma(1/s)} \text{ and } A = \frac{sB}{\Gamma(1/s)}, \tag{14}$$

where $\Gamma(p)$ is the gamma function given by $\int_0^\infty x^{p-1}\exp(-x)\,dx$, and

$$s = p - n + 2. \tag{15}$$

From the relationship for plume variance (i.e. $\sigma_z^2 = \int z^2 Cdz / \int Cdz$) the mean plume height, $\bar{z}$, is related to plume spread by

$$\sigma_z = f_z\bar{z}, \tag{16}$$

where $f_z = \left(\frac{\Gamma(3/s)}{\Gamma(1/s)}\frac{1}{B^2}\right)^{1/2}$. Substituting Equations (10) and (12) into Equation (13) results in

$$\bar{U} = f_u U_r\left(\frac{\bar{z}}{z_r}\right)^p = f_u U(\bar{z}), \tag{17}$$

$$\text{where } f_u = \Gamma\left(\frac{p+1}{s}\right)\Big/\left[\Gamma\left(\frac{1}{s}\right)B^p\right].$$

The important result that is used in the subsequent analysis can be derived from the previous equations (van Ulden 1978):

$$\frac{d\bar{z}}{dx} = sB^s\frac{K(\bar{z})}{U(\bar{z})\bar{z}}. \tag{18}$$

Because $\bar{z}$ is related to the plume σ_z through Equation (16), the result (18) becomes the primary equation to estimate plume spread. As in van Ulden (1978), we will assume that Equation (18) holds even when Equation (15) is not satisfied. The justification is provided by the results obtained by van Ulden (1978).

To make progress, we will assume that at the asymptotic limits of neutral, stable, and unstable conditions, the eddy diffusivity can be written as $K(z) = \alpha u_* z^n |L|^{1-n}$, where α is a constant. Note $n=1$ represents neutral conditions, $n=0$ to very stable conditions, and $n=3/2$ to very unstable conditions.

Then, if we substitute Equations (10) and (11) into Equation (18) and integrate, we find

$$\bar{z} \sim \left[\frac{u_*}{U_p} x |L|^{1-n} z_m^p\right]^{\frac{1}{(p+2-n)}}, \tag{19}$$

which reduces, using Equation (10), to

$$\bar{z} \sim \left[\frac{u_*}{U(\bar{z})} x |L|^{1-n}\right]^{\frac{1}{(2-n)}}. \tag{20}$$

Note that Equation (20) is implicit in $\bar{z}$ because U is evaluated at $\bar{z}$. We compute the wind speed at the mean plume height by solving the following equation iteratively,

$$\sigma_z = f\left(x, u_*, L, U(\bar{z})\right), \tag{21}$$

where the mean plume height for a Gaussian distribution is given by

$$\bar{z} = \sigma_z \sqrt{\frac{2}{\pi}} exp\left[-\frac{1}{2}\left(\frac{z_s}{\sigma_z}\right)^2\right] + z_s erf\left(\frac{z_s}{\sqrt{2}\sigma_z}\right). \tag{22}$$

From Equation (22) the mean plume height depends on the vertical spread.

3.1 Vertical Spread, σ_z

To obtain an expression for σ_z for neutral conditions (n=1), we use the relationship between σ_z and $\bar{z}$ (from Equation (16))to reduce Equation (20) to:

$$\sigma_z = a\frac{u_* x}{U_e}, \tag{23}$$

where a is a constant that is evaluated empirically. In applications of this model, U_e is substituted for $U(\bar{z})$, see Equation (5).

The stable velocity asymptote $U(\bar{z}) \sim u_* \bar{z}/L$ leads to $\sigma_z \sim L^{2/3} x^{1/3}$ and an equation that interpolates between the neutral and stable limits becomes

$$\sigma_z = a\frac{u_*}{U_e} x \frac{1}{\left(1 + b_s \frac{u_*}{U_e}\left(\frac{x}{|L|}\right)^{2/3}\right)}. \tag{24}$$

To derive the unstable σ_z asymptote, we take $n=3/2$, and obtain

$$\sigma_z \sim (u_*/U_e)^2 x^2/|L|, \tag{25}$$

and the semi-empirical formulation for σ_z under unstable conditions becomes

$$\sigma_z = a\frac{u_*}{U_e}x\left(1 + b_u\left(\frac{u_*}{U_e}\frac{x}{|L|}\right)\right). \tag{26}$$

Note that these expressions for σ_z are implicit because the wind speed, U_e, on the right hand side of the equation is a function of $\bar{z}$, which in turn is a function of σ_z.

Briggs (1982) and Venkatram (1982; 1992) used a similar approach to connect the asymptotic limits of the crosswind integrated concentrations. But they used the expression for the crosswind concentration to derive the expression for the vertical plume spread rather than connecting the asymptotes of the actual plume spreads, as we have done here. This explains the difference between the current formulation and the earlier ones.

3.2 Horizontal Spread, σ_y

Estimates of horizontal dispersion in the surface layer are largely based on Taylor's theory (1921) for dispersion in homogeneous turbulence based on a Lagrangian time scale, i.e. travel time. However, travel time cannot be defined unambiguously because the wind speed varies with height, therefore there is no theoretically justified choice for the Lagrangian time scale.

Equations currently in use for σ_y, such as those proposed by Irwin (1983) and Draxler (1976), use the wind speed at a specific height, usually the source height, to estimate the travel time and the Lagrangian time scale is a purely empirical fit. Eckman (1994) showed that the variation of σ_y with distance, the initial linear increase followed by a smaller increase with distance (or travel time) could be explained by the increase of the wind speed with height if one assumed that σ_y is governed by the small time expression

$$\frac{d\sigma_y}{dx} = \frac{\sigma_v}{\bar{U}}. \tag{27}$$

where σ_v is the standard deviation of the horizontal velocity fluctuations, even when it does not vary with height, and the mean plume velocity, $\bar{U}$, is defined by the Equation (13).

Using a numerical solution of Van Ulden's (1978) expression for $\bar{z}$, Eckman (1994) showed that Equation (27) provides an excellent description of horizontal spread data from a variety of studies. Thus, Eckman's formulation avoids the arbitrariness entailed in specifying travel time and it also incorporates our current understanding of the effects of stability on dispersion. Eckman (1994) provides a useful analytical approximation for σ_y based on the numerical integration of Equation (27). In this paper, we adopt Equation (27) to derive expressions for the horizontal spread, σ_y. We integrate Equation (27) using Equations (17) and (20) to obtain

$$\sigma_y \sim \frac{\sigma_v}{u_*}\sigma_z\left(\frac{\sigma_z}{|L|}\right)^{1-n}. \qquad (28)$$

taking $\bar{z}$ as a constant fraction of σ_z. An expression for σ_y that interpolates between the neutral and very stable and unstable conditions is given by

$$\sigma_y = c\frac{\sigma_v}{u_*}\sigma_z\left(1+d\frac{\sigma_z}{|L|}\right)^{1-n}, \qquad (29)$$

where *c* and *d* are empirical constants; the value of *d* depends on the sign of *L*. Note that the wind speed and the vertical and horizontal spreads that appear in the equation to compute concentration depend on each other, and cannot be calculated independently.

3.3 Evaluation of plume spread equations with Prairie Grass and Idaho Falls data

We can evaluate the empirical constants in the vertical spread equations, (24) and (26), at Prairie Grass and Idaho Falls by comparing the measured and modeled crosswind integrated concentrations. The measurements from a finite line source (54 meters) at Idaho Falls were converted to those corresponding to an equivalent infinite line source using an approach described in (Heist et al. 2009). C_y, the crosswind integrated concentrations, is inversely proportional to σ_z when scaled with u*, L and Q. Since σ_z is a strong function of x/|L| and a weaker function of u_*/U_e, Figure 4 shows a comparison of the normalized concentration (C_y) as a function of x/|L| for values of u_*/U_e that are representative of the range of observations in the two field studies. Based on this analysis the coefficients from Eqn. (24) and (26) that best represent these data sets are a = 0.57, $b_s = 1.5$ and $b_u = 0.5$.

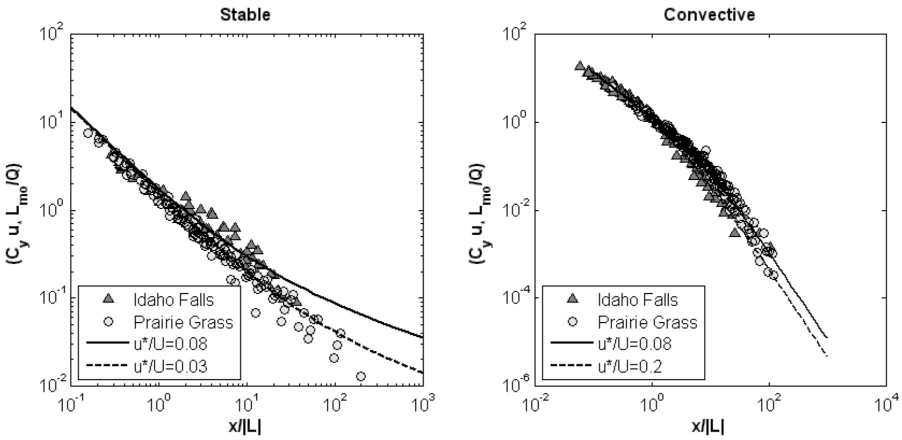

Figure 4: Idaho Falls 2009(▲) and Prairie Grass (○) normalized concentration vs. $x/|L|$. The solid and dashed lines represent Equation (24), for stable, and Equation (26), for convective, with u_*/U_e values representative of the range of values in the field studies.

We further test this new vertical dispersion formulation by using measured σ_z from the wind tunnel studies. A series of wind tunnel experiments were performed in EPA boundary-layer wind tunnel (Heist et al. 2009) to examine the effect of roadway configurations (including noise barriers and roadway depression relative to the surrounding terrain) on the dispersion of traffic-related pollutants. The data for a flat roadway are used here in evaluating the vertical dispersion formulations. Vertical concentration fields (typically unavailable in field studies) are particularly useful for estimating vertical dispersion.

In Figure 5 the measured σ_z values from the wind tunnel experiment are shown with the calculated σ_z using Equation (26) at the neutral limit. We assume that the emissions are at a height of 0.9 m with $\sigma_{z0} = 0.4$ m. (based on the size of the roughness elements on the model roadway). The apparent offset between the modeled and measure σ_z is likely to be from the initial mixing near the source. However, this figure shows agreement between the measured and calculated vertical dispersion growth rates.

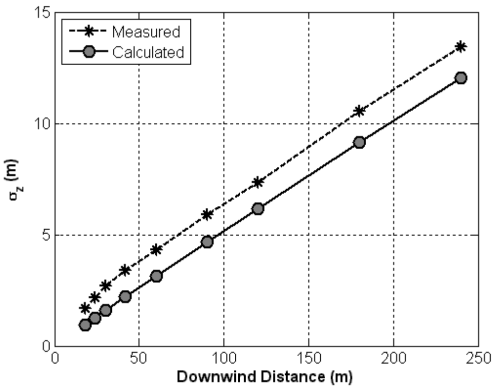

Figure 5: Calculated and measured wind tunnel σ_z as a function of downwind distance. The σ_z was calculated with a source height of 0.9 m and an initial σ_z of 0.4 m.

For the horizontal dispersion formulation (29), we used the Prairie Grass data to determine the coefficients. The σ_y's were determined by fitting a Gaussian distribution to the concentrations measured at each downwind distance. Based on the comparison of Equation (29) for σ_y with these estimates, the coefficients that best represent these data were found to be $c = 1.6$ (for all conditions) and $d = 2.5$ for stable conditions and $d = 1$ for convective conditions.

The comparisons of model to data using these coefficients are shown in Figure 6. Overall, these new horizontal dispersion formulations produce geometric mean values near unity for all stabilities and nearly all of the estimated σ_y values are within a factor of two of the observed values. In addition, comparison of Figures 2 and 6 shows that the new horizontal spread equations describe the data considerably better than the empirical Equation (3).

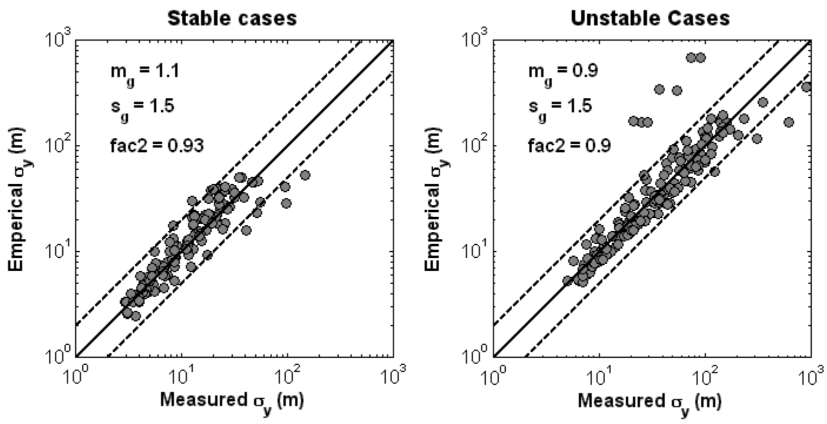

Figure 6: Comparison of σ_y estimates from new equations (30b and 31b) with measured values from the Prairie Grass field study.

The constants that provide the best fit between model estimates for the vertical spread are:

$$\sigma_z = 0.57\frac{u_*}{U_e}x\left(1+3\frac{u_*}{U_e}\left(\frac{x}{L}\right)^{2/3}\right)^{-1} \quad \text{for } L > 0.0$$

$$= 0.57\frac{u_*}{U_e}x\left(1+1.5\left(\frac{u_*}{U_e}\frac{x}{|L|}\right)\right) \quad \text{for } L < 0.0\,; \tag{30}$$

and for the horizontal spread are:

$$\sigma_y = 1.6\frac{\sigma_v}{u_*}\sigma_z\left(1+2.5\frac{\sigma_z}{L}\right) \quad \text{for } L > 0.0$$

$$= 1.6\frac{\sigma_v}{u_*}\sigma_z\left(1+\frac{\sigma_z}{|L|}\right)^{-1/2} \quad \text{for } L < 0.0. \tag{31}$$

A comparison of Figures 1 and 7 shows the new formulations for plume spreads yield concentration estimates that compare better with observed values (at Prairie Grass) than those based on the earlier equations (2) and (3).

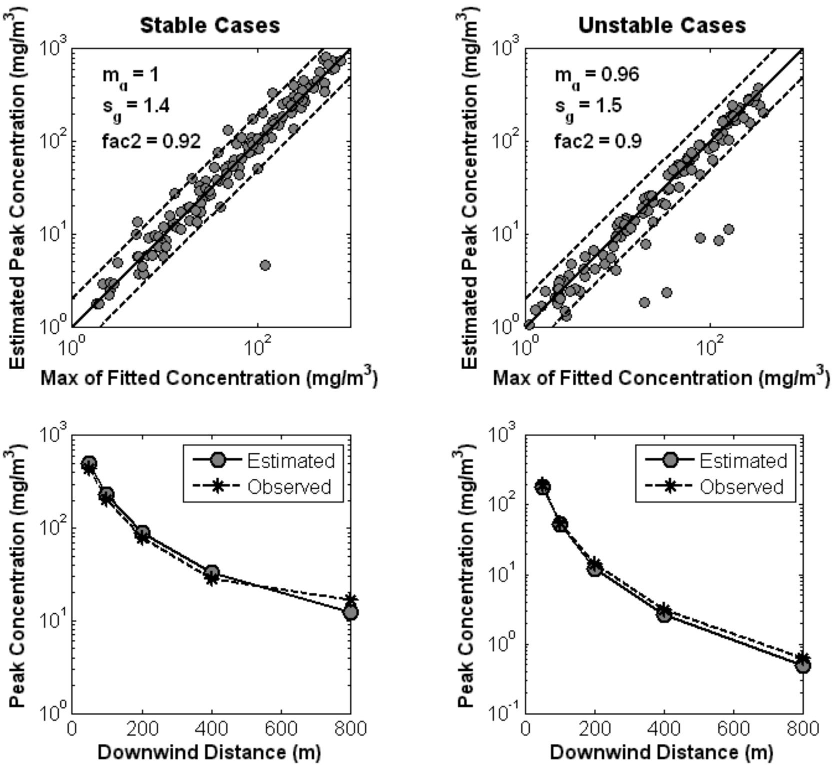

Figure 7: Comparison of concentration estimates from new equations (30) and (31) to observations at Prairie Grass. Bottom panel compares mean of the maximum estimated concentrations at each downwind distance with corresponding observations.

As Figure 3 indicates for Idaho Falls, Equations (2) and (3) applied within the RLINE model yield concentration estimates that show systematic biases relative to the observed values. These biases are reduced substantially in the results corresponding to Equations (30) and (31) as seen by comparing Figure 3 and 7. Looking at the concentration profile as a function of downwind distance (Figure 9) the new formulations, provide improvement. However, concentrations are still underestimated particularly for the very stable cases. This underestimation is substantially reduced if RLINE is run without the meander algorithm, which suggests that the treatment of wind meander might require modification.

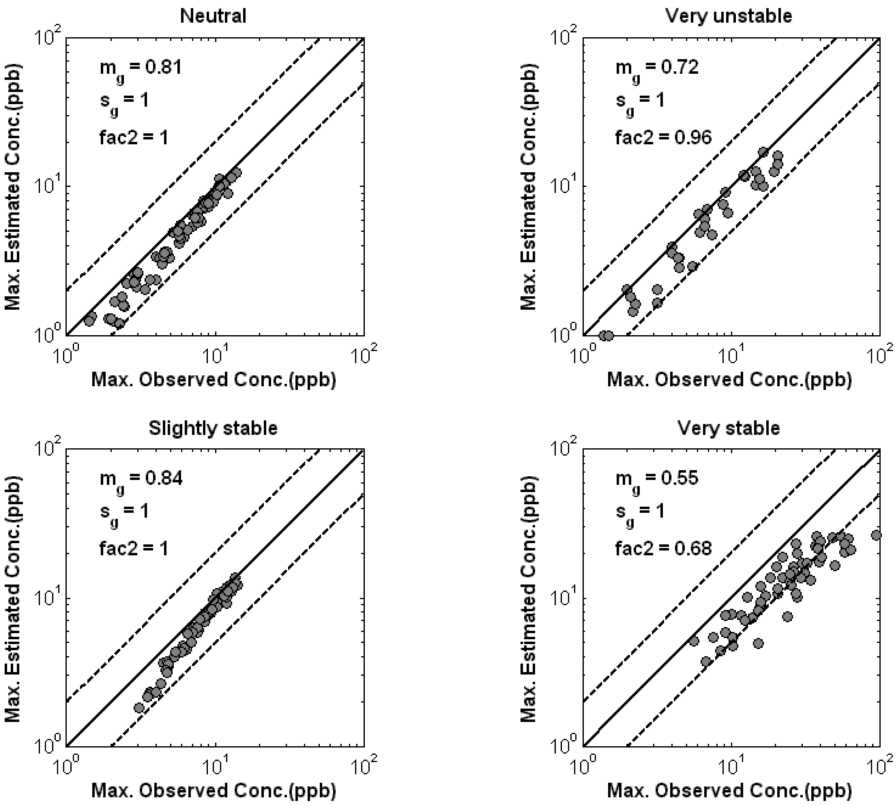

Figure 8: Comparison of maximum concentration estimates based on new dispersion equations (30) and (31) with corresponding observations from Idaho Falls. Parallel lines denote factor of two intervals.

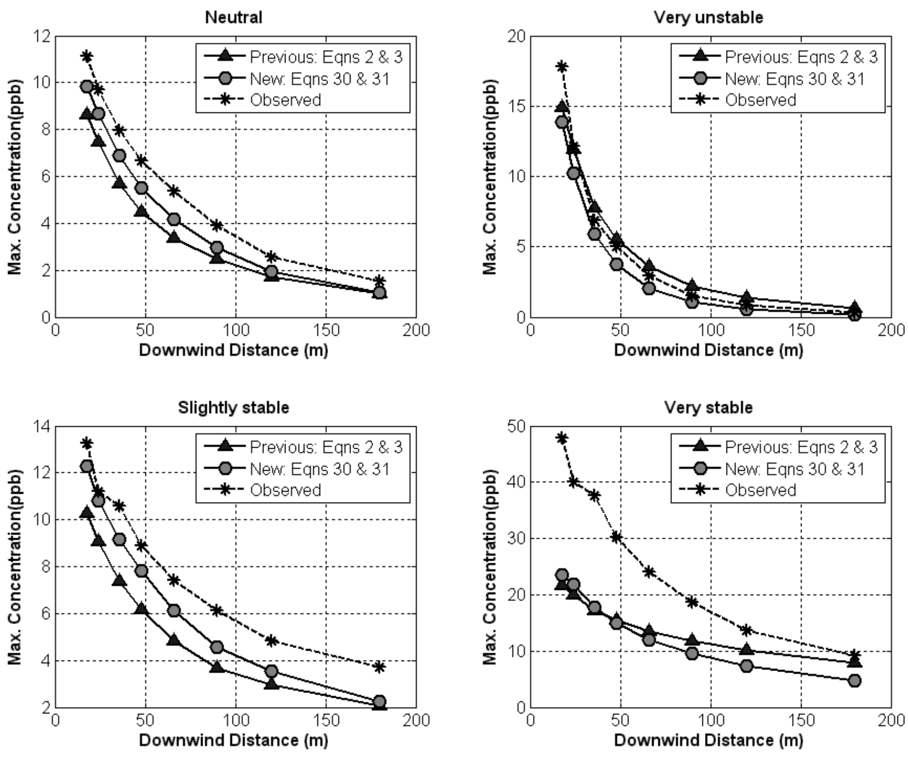

Figure 9: Comparison of mean maximum modeled concentrations at each downwind distance with corresponding observations at Idaho Falls.

4 Summary

Results from a recently conducted field study in Idaho Falls (Finn et al. 2010) allowed us to re-examine dispersion formulations for near-surface releases. This paper proposes new formulations for horizontal and vertical plume spread for releases in the near surface boundary layer. The equations for vertical spread are functions of downwind distance and surface micrometeorological variables including surface friction velocity and Monin-Obukhov length. The theoretical foundation of these equations is the mass conservation equation expressed in terms of the eddy diffusivity based on surface layer similarity. This approach has been demonstrated by Van Ulden (1978) and others (Gryning et al. 1983) to provide an excellent description of dispersion of surface releases.

The horizontal plume spread equations are based on Eckman's (1994) suggestion that horizontal plume spread is governed by horizontal turbulent velocity fluctuations and the vertical variation of the wind speed at mean plume height. The resulting equations explicitly relate horizontal plume spread to vertical plume spread, and do not contain any references to a Lagrangian time scale, which is often used in currently used formulations (Irwin, 1983 for example). The new equations for horizontal plume spread yield estimates that compare well with observations from the Prairie Grass experiment.

Concentration estimates based on the proposed plume spread equations compare well with data from the Prairie Grass experiment (Barad 1958) as well as the recently conducted Idaho Falls experiment (Finn et al. 2010). One of the major conclusions of this study is that the plume spreads as well as the wind speed used to estimate concentrations are variables that need to be consistent with each other.

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6 Disclaimer

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