REFORMULATION OF PLUME SPREAD FOR NEAR-SURFACE DISPERSION

Akula Venkatram[1], Michelle Snyder[2], David Heist[2], Steven Perry[2], Vlad Isakov[2]

[1]University of California, Riverside, CA 92521 USA

[2]Atmospheric Modeling and Analysis Division, National Exposure Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Research Triangle Park, NC 27711 USA

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. This examination led to the 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-road concentrations, surface releases, similarity theory, model performance, Prairie Grass experiment, Idaho Falls experiment*

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. In response to this concern with the health effects, the USEPA conducted a tracer field study (Finn et al., 2010) designed to understand the impact of barriers on dispersion from line sources. In this study, SF_6, the tracer, was released simultaneously from two 54 m line sources at a height of 1 m to simulate emissions from near surface releases. A 6 m barrier was placed in front of the line sources. The concentrations associated with each of these sources were sampled with a grid of 58 samplers at 1.5 m above ground at distances of 18 m to 180 m from the line source. Measurements made with sonic anemometers provided 10 Hz velocity and temperature measurements. The data from the experiment without the barrier was used to evaluate plume dispersion equations (Briggs, 1982; Venkatram, 1992) based on the Prairie Grass experiment. The results indicated that the dispersion curves did not describe the Idaho Falls data as well as it did for Prairie Grass. This led to a reformulation of the equations used to estimate plume spread of surface releases. These equations describe the concentrations observed at both Prairie Grass as well as Idaho Falls.

CURRENT FORMULATION

The plume spread formulations used in AERMOD (Cimorelli et al., 2005) are representative of those used in the current generation of dispersion models. The vertical spread, σ_z, which is similar to that proposed by Briggs (1982), is based on Venkatram (1982,1992):

$$\begin{aligned}\sigma_z &= \sqrt{\frac{2}{\pi}}\frac{u_* x}{U}\left(1+0.7\frac{x}{L}\right)^{-1/3} \quad L>0.0 \\ &= \sqrt{\frac{2}{\pi}}\frac{u_* x}{U}\left(1+0.006\left(\frac{x}{|L|}\right)^{2}\right)^{1/2} \quad L<0.0\end{aligned}, \qquad (1)$$

where L is the 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 equation for horizontal spread used in AERMOD (Cimorelli et al., 2005) is a purely empirical equation that fits the data from Prairie Grass. The comparison between concentration estimates, based on currently used plume spreads, and concentrations made at the samplers in the Idaho Falls experiment showed that 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. These results motivated a reexamination of the plume dispersion equations.

REFORMULATION OF PLUME SPREAD EQUATIONS

The result that is used in the subsequent analysis was derived by van Ulden (1978):

$$\frac{d\overline{z}}{dx} = A\frac{K(\overline{z}\,)}{U(\overline{z}\,)\overline{z}}\,, \qquad (2)$$

where the mean plume height $\overline{z}$ is related to the plume σ_z, *K(z)* is the eddy diffusivity for heat, the wind speed *U* is evaluated at the mean plume height, and *A* is a constant. At the asymptotic limits of neutral, stable, and unstable conditions, the eddy diffusivity can be written as $K\left(z\right) = \alpha u_* z^n \left|L\right|^{1-n}$ where α is a constant; *n=1* represents neutral conditions, *n=0* to very stable conditions, *n=3/2* to very unstable conditions. Then, if we assume that the wind speed is of the form $\propto z^p$ and substitute the asymptotic expressions for *K(z)* into Equation (2) and integrate, we find

$$\overline{z} \sim \left[\frac{u_*}{U} x L^{1-n}\right]^{\frac{1}{(2-n)}}. \qquad (3$$

The stable velocity asymptote $U \propto u_* \overline{z} / L$ leads to $\sigma_z \sim L^{2/3} x^{1/3}$ and the formula that interpolates between the neutral and stable limits becomes

$$\sigma_z = a\frac{u_*}{U} x \frac{1}{\left(1 + b_s \dfrac{u_*}{U}\left(\dfrac{x}{L}\right)^{2/3}\right)}. \qquad (4)$$

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

$$\sigma_z = a\frac{u_*}{U} x \left(1 + b_u\left(\frac{u_*}{U}\frac{x}{L}\right)\right). \qquad (5)$$

Note that these expressions for σ_z are implicit because the wind speed, *U*, on the right hand side of the equation is a function of $\overline{z}$, 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.

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

$$\frac{d\sigma_y}{dx} = \frac{\sigma_v}{U} \qquad (6)$$

Where σ_v is the standard deviation of the horizontal velocity fluctuations, even when it does not vary with height, and the transport wind speed, U, is evaluated at $\overline{z}$. Because $\overline{z}$ is related to σ_z, we can evaluate *U* using the asymptotic expressions for σ_z, and integrate Equation (6) to obtain

$$\sigma_y \sim \frac{\sigma_v}{u_*}\sigma_z\left(\frac{\sigma_z}{|L|}\right)^{1-n}. \qquad (7)$$

The plume spread equations with the empirical constants that provide the best fit between model estimates and observations are listed below. For stable conditions:

$$\sigma_z = 0.57\frac{u_*}{U}x\left(1+3\frac{u_*}{U}\left(\frac{x}{L}\right)^{2/3}\right)^{-1} \qquad (8a)$$

$$\sigma_y = 1.6\frac{\sigma_v}{u_*}\sigma_z\left(1+2.5\frac{\sigma_z}{L}\right), \qquad (8b)$$

and the semi-empirical formulations for unstable conditions are

$$\sigma_z = 0.57\frac{u_*}{U}x\left(1+1.5\left(\frac{u_*}{U}\frac{x}{|L|}\right)\right), \qquad (9a)$$

$$\sigma_y = 1.6\frac{\sigma_v}{u_*}\sigma_z\left(1+\frac{\sigma_z}{|L|}\right)^{-1/2}. \qquad (9b)$$

EVALUATION OF PLUME SPREAD EQUATIONS WITH PRAIRIE GRASS AND IDAHO FALLS DATA

Figure 1 shows that these equations yield estimates of horizontal plume spread that compare better with observed values than those based on the earlier purely empirical equation for horizontal plume spread derived from Prairie Grass data.

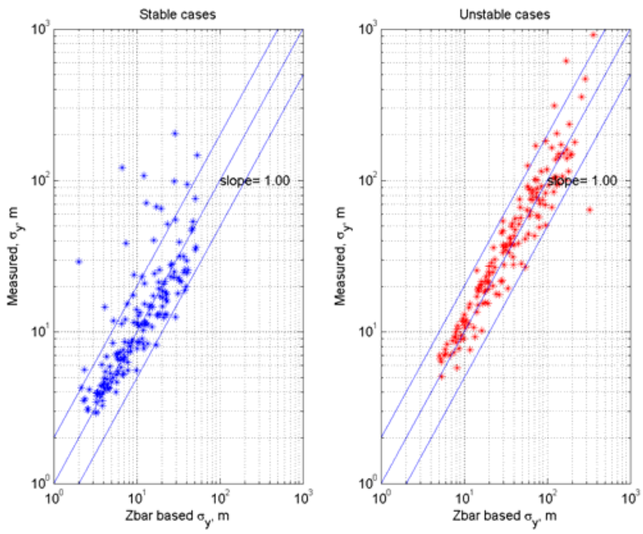

Figure 1: Comparison of σ_y estimates from new equations (8) and (9) with values derived from Prairie Grass concentration measurements.

Figure 2 shows that the new equations (8) and (9) provide good descriptions of maximum concentrations measured at Idaho Falls. In summary, the new formulations for vertical and horizontal plume spread in the surface boundary layer have a better theoretical foundation than that of currently used equations, and they also provide better descriptions of plume spreads and tracer concentrations measured at the Prairie Grass (Barad, 1958) and Idaho Falls (Finn et al., 2010) field experiments.

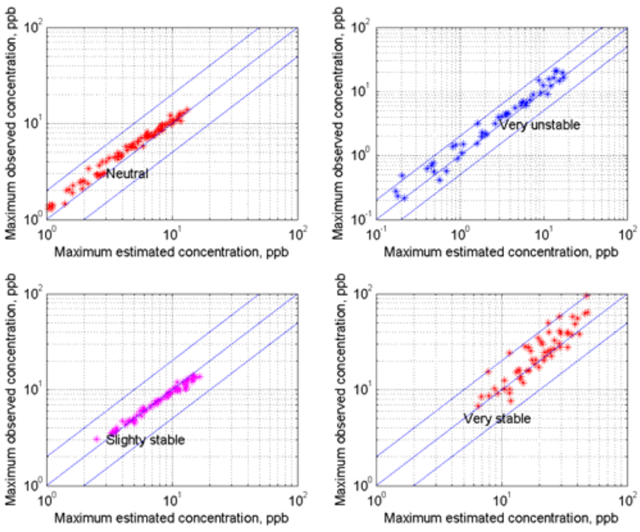

Figure 2: Comparison of maximum concentration estimates based on new plume dispersion Equations (8) and (9) with corresponding observations from Idaho Falls. Parallel lines represent factor of two intervals.

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