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A SURFACE DEPLETION MODEL FOR DEPOSITION FROM A GAUSSIAN PLUME

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ABSTRACT

When the atmospheric diffusion of a material is described by the usual Gaussian plume model, dry deposition of the contaminant onto the underlying surface is commonly accounted for by appropriately reducing the source strength, as originally proposed by Chamberlain. A more realistic model is developed which selectively depletes the Gaussian plume in the vicinity of the deposition surface rather than throughout the vertical extent of the plume as done in the source depletion model. This improved model is used to show that the source depletion model consistently overpredicts the surface air concentration and the deposition at downwind locations close to the source and, as a consequence, is biased in the opposite sense for locations far from the source. At all distances from the source, the source depletion model overestimates the total deposition between source and receptor and consequently underpredicts the amount of remaining airborne material. Quantitative comparisons are shown to aid the user in choosing, for his particular circumstances, between the less accurate source depletion model and the computationally more complex surface depletion model.

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INTRODUCTION

Dry deposition of an airborne material onto the underlying surface is of interest from two different standpoints. First of all, it can be an important sink for the material, reducing air concentrations (and consequent dry deposition) further downwind. In the case of a noxious substance this is beneficial to downwind receptors. However, dry deposition secondly is a mechanism for accumulation of the material on the ground and hence is a detrimental process at the point of deposition. Since a high estimate for the deposition flux will be conservative at the point of deposition and, at the same time, non-conservative downwind of that point, modeling of the dry deposition process should be unbiased. However, it will be shown here that the source depletion model currently used for predicting deposition from the Gaussian plume is biased. This will be done by developing a surface depletion model which eliminates the artificial basis of the former model and comparing the predictions of the two models. The biases of the source depletion model will be quantitatively delineated in order to provide a basis for choosing, in a specific situation, between the less accurate source depletion model and the computationally more complex surface depletion model.

THE DEPOSITION VELOCITY

The deposition of airborne material onto the underlying surface can be caused by a combination of mechanical processes (gravitational settling, turbulent and molecular diffusion, inertial impaction) and is often further complicated by electrical and chemical effects or the existence of heat and moisture fluxes normal to the deposition surface. In the absence of detailed

microphysical measurements, the deposition flux F_d is usually assumed to be directly proportional to the local air concentration evaluated at a reference height z_d ,

$$F_d(x,y) = v_d \chi(x,y,z_d) \quad (1)$$

The constant of proportionality v_d has the dimensions of a velocity and has been appropriately named the deposition velocity. For common aerosols v_d

can vary from about 10^{-4} to 10^0 cm/sec depending on specific properties of the particles, of the atmospheric structure, and of the deposition surface. (1)

Most of the results to be presented here, however, are parameterized only by the ratio of the deposition velocity to the mean wind speed, $v_d/\bar{u}$. Since $\bar{u}$ in the lowest 100m of the atmosphere is commonly in the range of 1-10m/s, $v_d/\bar{u}$ can vary from about 10^{-6} to 10^{-1} .

SOURCE DEPLETION MODEL

The atmospheric diffusion process will be described by the standard Gaussian plume model for a non-depositing material, incorporating "reflection" of the material at the ground to insure conservation of mass. For that purpose we define a diffusion function $D(x,y,z,h)$:

$$D(x,y,z,h) \equiv \frac{\chi(x,y,z)}{Q} = \frac{e^{-y^2/2\sigma_y^2}}{2\pi\sigma_y\sigma_z\bar{u}} \left\{ \exp \left[\frac{-(h-z)^2}{2\sigma_z^2} \right] + \exp \left[\frac{-(h+z)^2}{2\sigma_z^2} \right] \right\} \quad (2)$$

where $\chi(x,y,z)$ is the downwind air concentration due to a continuous source of strength Q located at the point $(0,0,h)$. The source depletion model, (2)

then, accounts for the loss of airborne material due to deposition by appropriately reducing the source strength as a function of downwind distance, i.e.,

$$\chi(x,y,z) = Q(x) D(x,y,z,h) \quad (3)$$

Conservation of mass requires that:

$$\begin{aligned} \frac{dQ(x)}{dx} &= - \int_{-\infty}^{\infty} v_d \chi(x,y,z_d) dy \\ &= -v_d Q(x) \bar{D}(x,z_d,h) \end{aligned} \quad (4)$$

where

$$\bar{D}(x,z,h) = \frac{1}{\sqrt{2\pi} \sigma_z \bar{u}} \left\{ \exp \left[\frac{-(h-z)^2}{2\sigma_z^2} \right] + \exp \left[\frac{-(h+z)^2}{2\sigma_z^2} \right] \right\} \quad (5)$$

Thus

$$Q(x) = Q_0 \exp \left\{ - \int_0^x v_d \bar{D}(\xi, z_d, h) d\xi \right\} \quad (6)$$

where Q_0 is the undepleted source strength at $x = 0$. Note that although the source depletion model correctly determines the deposition flux in terms of the air concentration near the surface $\chi(z = z_d)$, it also instantaneously distributes the effect of the deposition throughout the entire vertical extent of the plume. Retaining the Gaussian shape of the plume thus artificially enhances the vertical diffusion. The qualitative and quantitative results of this effect will be seen below.

SURFACE DEPLETION MODEL

A more realistic approach is provided by the surface depletion model. In the development of this model, advantage is taken of the fact that the linearity of the differential equation describing gradient diffusion allows the superposition of solutions such as Eq. (2). The deposition flux to the surface is represented as a material sink, i.e., a negative source for downwind diffusion from the point of deposition. Thus deposition at the point $(\xi, \eta, 0)$ will effect a reduction of the air concentration at the downwind point (x, y, z) equal to:

$$\left[-v_d \chi(\xi, \eta, z_d) d\xi d\eta \right] D(x-\xi, y-\eta, z, 0) \quad (7)$$

where the bracketed quantity is an areal source strength due to deposition. The air concentration at any point can then be calculated as the sum of the nondepositing diffusion from the primary source at $(0, 0, h)$ plus the diffusion from all of the upwind surface sources which account for deposition,

$$\chi(x, y, z) = Q_0 D(x, y, z, h) - \int_{-\infty}^{\infty} \int_0^x v_d \chi(\xi, \eta, z_d) D(x-\xi, y-\eta, z, 0) d\xi d\eta \quad (8)$$

This equation and the subsequent calculations can be considerably simplified if we consider the cross-wind-integrated air concentration:

$$\bar{\chi}(x, z) = Q_0 \bar{D}(x, z, h) - \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_0^x v_d \chi(\xi, \eta, z_d) D(x-\xi, y-\eta, z, 0) d\xi d\eta dy \quad (9)$$

Performing, in succession, the integrations over y and η yields:

$$\chi(x, z) = Q_0 \bar{D}(x, z, h) - \int_0^x v_d \chi(\xi, z_d) \bar{D}(x-\xi, z, 0) d\xi \quad (10)$$

For the purpose of comparison, a similar equation may be written for the source depletion model:

$$\bar{x}(x,z) = \left[Q_0 - \int_0^x v_d \bar{x}(\xi, z_d) d\xi \right] \bar{D}(x,z,h) \quad (11)$$

This is equivalent to Eqs. (3) and (6), but comparison of the variables upon which $\bar{D}$ is functionally dependent in Eqs. (10) and (11) emphasizes the artificial assumption of the source depletion model that deposition is a loss at the source, $(0,0,h)$, rather than at the surface where it is actually occurring. The source depletion model, of course, is the easier model to apply since it retains the Gaussian distribution in the vertical and thus all of the effects of deposition are summarized in the single parameter $Q(x)/Q_0$. Further, Eq. (6) or (11) is much more economical to compute than Eq. (10) since the integrand of the deposition integral is not a function of the receptor coordinate x .

COMPARISON OF THE MODELS

Both models were applied to a variety of situations to assess the accuracy of the source depletion model relative to the surface depletion model and to provide information upon which to base a decision as to which model to use in a given situation. Some of the results of these calculations are shown in Fig. (1) - (4) which display, as a function of downwind distance from the primary source, the ratio between the air concentrations for a depositing material and for a nondepositing material, $(v_d = 0)$, as calculated by both the source depletion model and the surface depletion model. For the surface depletion model three ratios are shown: that of the air concentrations at a height of $1m, z_d$

at the source height, h , and vertically integrated over all heights. The latter curve, also called the suspension ratio, represents the fraction of the material which is still airborne or, subtracting from unity, the fraction deposited on the surface to that distance. As indicated in the model derivation, all three of these ratios are predicted for the source depletion model by the suspension ratio, $Q(x)/Q_0$. Calculations were made for three source heights: 2m, 10m, and 100m, and for three thermal stabilities: unstable (Pasquill A), neutral (Pasquill D) and stable (Pasquill F), using the rural diffusion coefficients amalgamated by Briggs.⁽³⁾ While these σ 's may already include the effects of deposition, they are entirely adequate for comparing the two deposition models. Note finally that the curves are parameterized with the ratio $v_d/\bar{u}$. It can be shown from the equations presented above that the ratio between the air concentration for a depositing and a nondepositing tracer is a function of the ratio $v_d/\bar{u}$ and not v_d and $\bar{u}$ independently.

Figs. (1) - (3) present results for $v_d/\bar{u} = 10^{-2}$, a case of moderately strong deposition, and for all combinations of thermal stability and source height. As discussed above, the assumptions of the source depletion model produce artificial vertical mixing of the plume. Since the vertical mixing due to real atmospheric processes decreases with increasing stability, the effects of the artificial mixing would be expected to become more noticeable as the thermal stability increases. It is easily seen from Fig. (1) - (3) that the differences between the two models do increase with increasing stability. Further, it is expected that the differences would decrease as the deposition decreases since the models are identical in the limit of

$v_d = 0$. This is demonstrated by comparing Fig. (4) for $v_d/\bar{u} = 10^{-3}$ and three combinations of height and stability with the corresponding cases in Figs. (1) - (3) for $v_d/\bar{u} = 10^{-2}$. For the source depletion model it can be shown that the relationship between the suspension ratios for different values of $v_d/\bar{u}$ is:

$$[Q(x)/Q_o]_a^{(v_d/\bar{u})_b} = [Q(x)/Q_o]_b^{(v_d/\bar{u})_a} \quad (12)$$

These figures show that the functional dependence of the surface depletion model on $v_d/\bar{u}$ is equally as strong.

As expected, the surface depletion model in general predicts smaller air concentrations at z_d than does the source depletion model. This is due to the fact that it realistically duplicates the actual physical situation by selectively depleting the portion of the plume adjacent to the surface rather than the entire vertical extent of the plume. Consequently, the surface depletion model also produces less deposition close to the source because the material deficit near the surface insulates the bulk of the plume from the deposition surface. Thus the surface depletion model always has a greater total quantity of airborne material. At large distances downwind of the source this has the effect of raising the near-surface air concentration of the surface depletion model until in some cases it eventually equals and surpasses that of the source depletion model. This occurs likewise for the dry deposition. These effects are best seen in Fig. (3) which presents the most extreme surface model/source model differences.

Figs. (2) and (3) also show the ratio of the air concentration at source height as predicted by the surface depletion model to that predicted by the Gaussian plume model without deposition. Especially for sources with a large release height this is close to the maximum concentration at any downwind distance. This variable is not shown in Fig. (1) and (4) due to the tight grouping of the curves. The only consistent relationship to be seen between this variable and the others shown is that the source height air concentration ratio is always greater than the reference height air concentration ratio as calculated by the surface depletion model. In most cases it is also less than the suspension ratio but since circumstances can always be found, e.g., large release height and strong stability, in which the deposition is not effectively communicated to the release height, it can also be greater than the suspension ratio.

CONCLUSIONS

Fig. (3) graphically displays the biases of the source depletion model: an overprediction of total deposition and a consequent underprediction of the remaining airborne material. For a case of moderately strong deposition, $v_d/\bar{u} = 10^{-2}$, and stable thermal stability the source depletion model is in error by factors of 3 to 4 for some parameters at a downwind distance of 10 km. These factors can become much larger at greater distances and for stronger deposition. Correspondingly, the differences between the models are sharply attenuated by decreasing $v_d/\bar{u}$ or decreasing the thermal stability. Fig. (4) shows the worst cases calculated for $v_d/\bar{u} = 10^{-3}$ from the set of

three release heights and three stabilities. The errors of the source depletion model are only 10-20%. Similarly for $v_d/\bar{u} = 10^{-2}$ and Pasquill A stability, the worst error is about 35%. Thus the source depletion model can be entirely adequate for a situation involving low deposition and grossly in error for a case of high deposition. The user must determine where the dividing line lies between these two extremes by carefully considering his own situation and requirements.

FIG. 1

Fig. 2

Fig. 3

Fig. 4

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