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The Long-distance "Transportable Fraction" of the Vertical Flux of wind-transported dust

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Introduction

A "lumped control volume" approach is used here to gain understanding of fugitive dust sources including wind erosion and road dust emission. This case considers dust generated from a road surface. By letting the road be directed into and out of the page while wind is directed from right to left we may invoke two-dimensionality or symmetry in the direction into the page (fluxes are equal into and out of the direction into the page). Figure 1 shows the geometry of our control volume. A dirt road exists at the right side of the control volume. To the left of the road is a surface that is grass or shrub-covered and does not emit particles. The ceiling of the control volume is the surface of primary interest as to vertical flux.

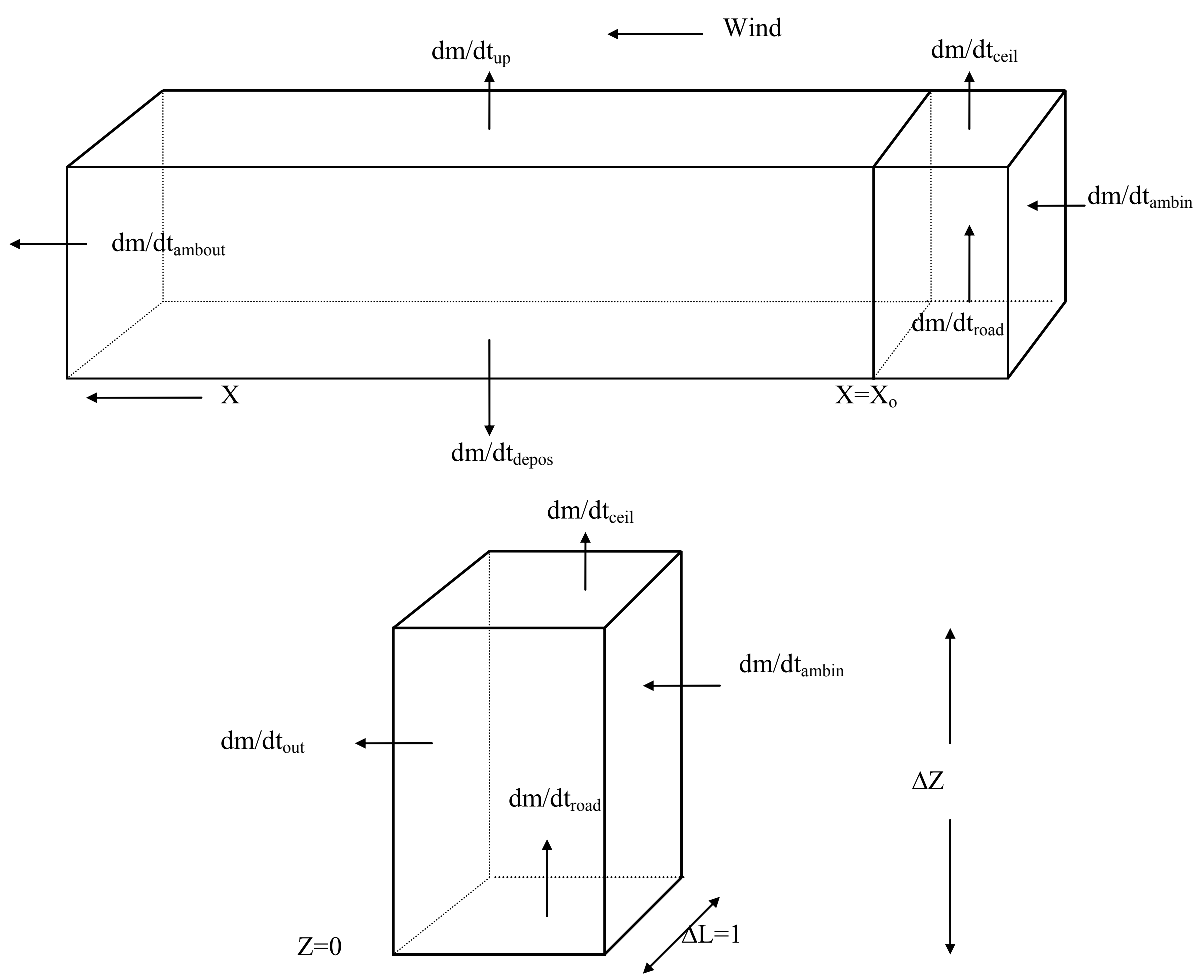

Figure 1. Control Volume for Fugitive Dust Model Depicting Vertical and Horizontal Fluxes. The quantities shown in the figure are as follows:

M is the mass of particles in the control volume (CV),
dm_{up}/dt is the mass per unit time passing out vertically at the top of the CV,
dm_{depos}/dt is the mass per unit time depositing to the floor of the CV,
dm_{ambout}/dt is the mass per unit time passing out of the CV through the left wall,
dm_{ambin}/dt is the mass per unit time passing into the CV from the right wall,
dm_{road}/dt is the mass per unit time emitted from the road, and
dm_{ceil}/dt is the mass per unit time passing out of the ceiling directly above the road.

A relation between the mass per unit time emitted from the road and the mass per unit time emitted from the road that can be considered to be regionally transported developed in the appendix is:

$$\Phi = \frac{\frac{dm_{up}}{dt}}{\frac{dm_{road}}{dt}} = \left[1 - \frac{V_d}{(V_d + K)}\right] = \frac{K}{(V_d + K)} \qquad (1)$$

(1)

We can evaluate the ratio Φ given by Equation 1 by making an approximation based on the data presented by Gillette (1974) that $K = 0.08u_*$ where u_* is the friction velocity. Using Equation 1 and the above expression for K, we can derive values of Φ for typical values of V_d where the values for u_* and V_d . Figure 2 shows families of Φ 's for differing V_d values. Values of V_d versus size and environmental conditions are given by Slinn (1982).

Discussion

The expression given in Equation 1 explains a large part of why observed concentrations are smaller than that predicted by regional scale models that do not correct for the large scale transportable vertical flux of dust but rather use the entire amount of dust emitted by roads. Because dust is deposited to the surface close to the source, uncorrected dust vertical fluxes lead to overestimates of dust concentrations downwind of the source. Other effects that are expected based on equation (1) are given below:

- For low wind speeds, little dust is input above the surface level of a roadway. This agrees with observations by Johnson, et al. (1992).
- For fugitive dust like downloading of sediment, Equation 1 overestimates Φ since horizontal diffusion would make more dust available for deposition to the ground. A correction for this would be to reduce the ratio Φ.
- For wind erosion, the threshold friction velocities are larger than 19 cm/s. Therefore, it would be expected that regional scale vertical flux of dust would be a very large fraction of field-scale flux of wind erosion dust.
- Dust devils, another class of fugitive dust sources, occur when the overall friction velocity is fairly low, but the height of the initial dust input is very high. For these conditions, the vertical flux dm_{up}/dt is virtually the same as for the input dust. Consequently, dust devils should be considered to be effective sources of dust. See Gillette and Sinclair (1989) for a discussion of dust devil dust fluxes.

Conclusion

A semiempirical model expresses in a simple expression the "transportable fraction of dust generated at ground level and carried by the wind.

Appendix: Derivation of Equation (1)

A conservation of mass equation can be written for the control volume shown in Figure 1 as:

$$dM/dt + dm_{up}/dt + dm_{depos}/dt + dm_{ambout}/dt - dm_{ambin}/dt - dm_{road}/dt + dm_{ceil}/dt = 0 \quad \text{(A-1)}$$

where, M is the mass of particles in the control volume (CV),
dm_{up}/dt is the mass per unit time passing out vertically at the top of the CV,
dm_{depos}/dt is the mass per unit time depositing to the floor of the CV,
dm_{ambout}/dt is the mass per unit time passing out of the CV through the left wall,
dm_{ambin}/dt is the mass per unit time passing into the CV from the right wall,
dm_{road}/dt is the mass per unit time emitted from the road, and
dm_{ceil}/dt is the mass per unit time passing out of the ceiling directly above the road.
A simplifying assumption is that of steady state emissions, that is, $dM/dt = 0$. For this case:

$$dm_{up}/dt = - dm_{depos}/dt - dm_{ambout}/dt + dm_{ambin}/dt + dm_{road}/dt - dm_{ceil}/dt \quad \text{(A-2)}$$

Relationship of mass per unit time to the horizontal mass flux from the road A subvolume of the control volume is shown in Figure 3-1 as that part that contains the road but no area downwind of the road. The left wall of this part of the control volume is the surface through which all of the dust emitted from the road passes. That is, we specify that none of the road dust is part of the ceiling flux (dm_{ceil}/dt). For the condition of steady state, a description of the conservation of mass for this part of the control volume is:

$$dm_{road}/dt = dm_{out}/dt - dm_{ambin}/dt + dm_{ceil}/dt \quad \text{(A-3)}$$

where dm_{out}/dt is the horizontal mass per unit time passing out through an imaginary wall just left of the left edge of the road reaching from the surface to the top of the control volume, and dm_{ceil}/dt is the mass per unit time passing through the ceiling of the control volume Because the road dust is usually the overwhelming source of dust, that is, $dm_{road}/dt >> dm_{ambin}/dt + dm_{ceil}/dt$ the horizontal flux dm_{out}/dt for these conditions is approximately:

$$dm_{road}/dt = dm_{out}/dt \quad \text{(A-4)}$$

which is the horizontal mass flux of dust from the road.

Deposition at the floor and vertical flux of dust through the ceiling of the control volume downwind of the road The total loss of material diffusing vertically through the ceiling and depositing on the floor of the control volume to the left of the road may be calculated by first calculating the effective concentration at position x to the left of x_0 (i.e., the left edge of the road). We use the equation:

$$V \frac{dC(x)}{dx} = \frac{-C(x)[V_d + K]}{\Delta z} \quad \text{(A-5)}$$

where, V is the wind speed that carries the dust through the control volume (CV),
C(x) is the concentration of dust mass at position x in the CV,
x is the horizontal position in the CV, increasing to the left,
z is the vertical position in the CV, increasing from the floor to the ceiling,
V_d is the deposition velocity, and

K is a coefficient having the dimensions of velocity.
A solution to Equation (3-5) is:

$$C(x) = \frac{\frac{dm_{road}}{dt}}{V\Delta z\Delta L}\exp - \left[\frac{[V_d + K]}{V\Delta z}(x - x_o)\right] \tag{A-6}$$

Multiplying C(x) by V_d ΔL (i.e., the deposition velocity times the unit length of the road) and integrating with respect to x from x = x_0 to x = ∞ gives:

$$\frac{dm_{depos}}{dt} = \frac{V_d \frac{dm_{road}}{dt}}{(V_d + K)} \tag{A-7}$$

By making the approximation that $dm_{ambout}/dt - dm_{ambin}/dt \approx 0$ and ignoring dm_{ceil}/dt we may rewrite equation (3-2) as:

$$\frac{dm_{up}}{dt} = \frac{dm_{road}}{dt} - \frac{dm_{depos}}{dt} \tag{A-8}$$

Watson (personal communication, 2000) stated that the condition $dm_{ambout}/dt - dm_{ambin}/dt \approx 0$ was observed in the field for a distance x of about 200 meters in the absence of any intervening dust sources.

Ratio of vertical flux of road dust into the atmosphere to the horizontal flux of road dust This ratio, expressed by the symbol Φ, is given by:

$$\Phi = \frac{\frac{dm_{up}}{dt}}{\frac{dm_{road}}{dt}} = \left[1 - \frac{V_d}{(V_d + K)}\right] = \frac{K}{(V_d + K)} \tag{A-9}$$

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