The Downwind Spread of an Initially Vertical Column of Particles in a Sheared Environment

RONALD E. STEWART

Atmospheric Environment Service, Downsview, Ontario, Canada M3H 5T4

JOHN D. MARWITZ

Department of Atmospheric Science, University of Wyoming, Laramie 82071

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ABSTRACT

The effects of particle fallspeeds on the downwind spread of initially vertical columns or curtains are examined in environments with wind shear. Sets of equations describing the column width as a function of time and distance below column top are derived by assuming, first, that the particles fall at a constant rate and, second, that particle fallspeed changes with time. These predictions are compared with measurements of a seeding curtain within a non-turbulent stratus cloud with high wind shear (0.017 s^{-1}). The comparison implies that differential fallspeed effects in a non-turbulent sheared environment can account for much of the spread of the curtains.

1. Introduction

Clouds are often seeded with a vertical curtain of dry ice pellets or droppable AgI flares released from aircraft. The ice crystals which result, evolve into a spectrum of sizes and hence fallspeeds. Some AgI flares appear to nucleate a steady source of ice crystals for several minutes.

A seeding experiment was conducted in a slowly ascending, non-turbulent stratus cloud containing severe shear (0.017 s^{-1}) during the Sierra Cooperative Pilot Project. The following theory was developed to explain the unexpectedly high ice crystal diffusion rates which were measured.

The width of a column is discussed in Section 2 for the simplified case of constant particle fallspeed in a region of constant wind shear. The more general case of particle fallspeed increasing with time is presented in Section 3. The model predictions are compared with the measurements.

2. Constant fallspeed case

Fig. 1 illustrates the evolution of an initially vertical column. The column consists of grains with negligible fallspeeds and new particles which are continually being formed throughout its depth. The new particles are assumed to have a constant fallspeed. The diagram was constructed by applying the basic particle trajectory equations. The column, containing grains of material with negligible fallspeeds, tilts with time in the wind shear. Particles having fallspeeds are downwind of the column of grains because the particles fall from regions having higher wind speeds. At each level, the oldest particles have fallen the farthest and are on the extreme downwind edge.

The width of the column is a function of height as well as time. At the top of the column, the width is zero and it asymptotically approaches its maximum value at lower heights. As shown in Fig. 1, the level at which the maximum width occurs decreases as time increases.

If a layer is characterized by constant shear α and the continuously produced particles have constant fallspeed U, the width W at distance below the column top ΔZ as a function of time t is

$$W = \frac{\alpha U t^2}{2}, \qquad t \leqslant \frac{\Delta Z}{U}, \tag{1}$$

$$W = \alpha \Delta Z t - \frac{\alpha(\Delta Z)^2}{2U}, \quad t > \frac{\Delta Z}{U}. \tag{2}$$

Eq. (1) is similar to the equation derived by Marshall (1953) to describe the trajectories of ice crystals produced by generating cells in sheared environments. The time restriction represents the time required for particles to fall from the top of the column to the level being considered. The first term in Eq. (2) is the distance the top of the column moves, relative to the level being considered and the second term accounts for fall of particles from the top of the column to the level of interest.

The widths, as a function of time and distance below column top predicted by Eqs. (1) and (2), are plotted in Fig. 2 for $\alpha = 0.01$ s^{-1} and $U = 1$ m s^{-1}. After particles have fallen from the top of the column to a particular level the slope of the curve begins to flatten.

3. Variable terminal velocity case

A more general situation in the atmosphere occurs

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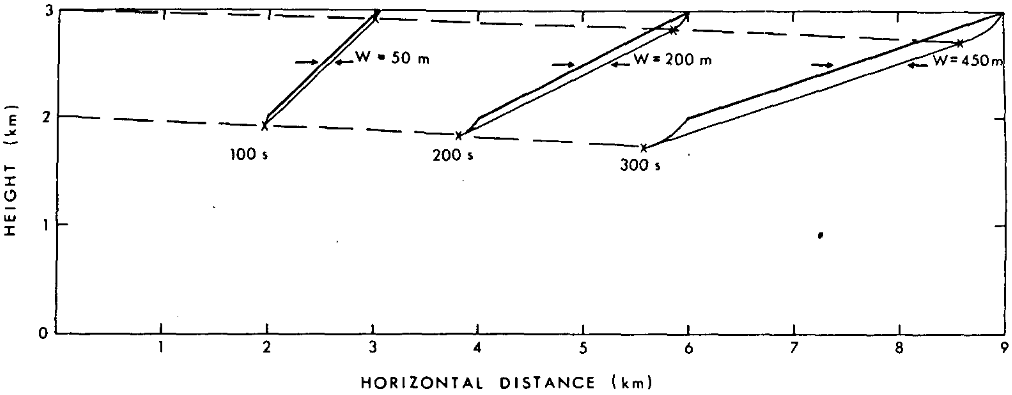

FIG. 1. Column shape as a function of time in a wind speed shear of 0.01 s^{-1}. The initial column is 1000 m deep and all particles fall at 1 m s^{-1} along similar trajectories to those indicated by dashed lines. The width W, at different times, is also shown.

when fallspeeds of particles increase with time. The consequences of this are examined below for a seeding experiment conducted in a stratiform cloud on 2 February 1980. New crystals, mainly plates, were continuously nucleated by AgI for over 30 min in this experiment. The fallspeed expression for plates growing at 1 μm s^{-1} (diameter) at a temperature of −12°C and pressure of 550 mb (Pruppacher and Klett, 1978) was assumed to be

$$U = 2 \times 10^{-3} t^{0.82}, \tag{3}$$

where U is in m s^{-1} and t is in s. Fallspeeds of 0.5 and 1.0 m s^{-1} are reached at 900 and 1800 s after formation, respectively. Halving the growth rate would roughly halve the rate of fallspeed increase.

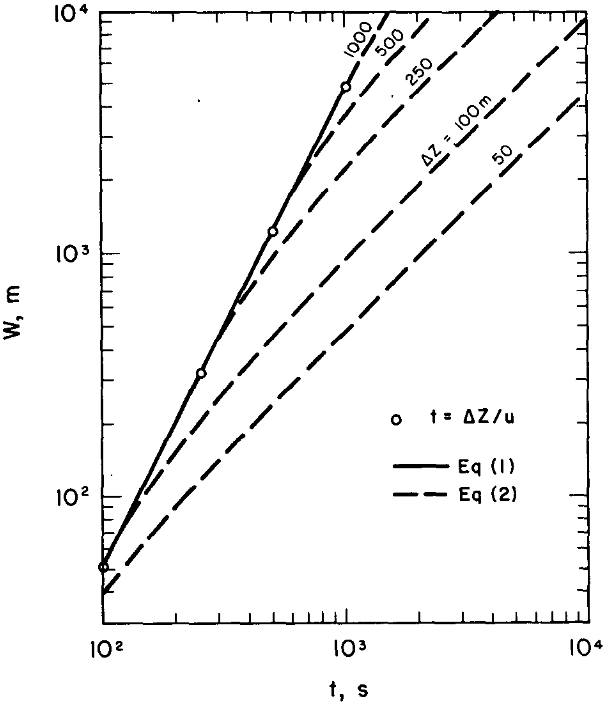

FIG. 2. Width (m) as a function of time and distance below column top for constant fallspeed. Fallspeed of the particles is 1 m s^{-1}, wind speed shear is 0.01 s^{-1}, and new particles are assumed to be produced continuously.

To determine the width of a column, the calculation of ice crystal trajectories fully incorporated the variable fallspeed assumption. As a result, the width of a column W (m) is approximately expressed as a function of time t (s), depth below column top ΔZ (m), and shear α (s^{-1}) as

$$W = 7 \times 10^{-4} \alpha t^{2.82}, \qquad t \leqslant 40(\Delta Z)^{0.55}, \tag{4}$$

$$W = \alpha \Delta Z t - 20\alpha(\Delta Z)^{1.52}, \qquad t > 40(\Delta Z)^{0.55}. \tag{5}$$

As shown by these equations, the width initially has a greater dependence on time than in the constant fallspeed case as expressed in Eq. (1).

Differentiating these equations leads to the rate of increase of width. In a shear of 0.01 s^{-1}, the column expands at 1.6 and 5.7 m s^{-1} at 500 and 1000 s, respectively, for levels > 300 m below column top [$t \leqslant 40(\Delta Z)^{0.55}$]. After particles have fallen from column top to a particular level, width increases are 1 and 10 m s^{-1} at 100 and 1000 m below column top, respectively. Such expansion rates are of the same order as those attributable to turbulent processes in convective clouds (Karacostas and Marwitz, 1980; Marwitz and Stewart, 1981; Rodi, 1981).

Fig. 3, which is based on Eqs. (4) and (5), illustrates the evolution of width for the variable fallspeed case in a shear of 0.01 s^{-1}. Comparing Figs. 2 and 3, it can be seen that at all times the width calculated under the assumption of constant fallspeed of 1 m s^{-1} was wider than that predicted under the assumption of increasing fallspeed arising from a 1 μm s^{-1} diameter growth rate. However, results from the two assumptions converge asymptotically at long times after seeding.

Predictions of width as a function of time for the seeding experiment on 2 February 1980 are also compared with measurements in Fig. 3. A shear of $\sim 0.017\ \mathrm{s}^{-1}$ was present from the seeding curtain top to the measurement level ~300 m below. Since Eqs. (4) and (5) show that the width is directly proportional to wind shear, measured widths have been multiplied by 0.6 (0.010/0.017) to allow an easy comparison with the predicted widths which were computed for a $0.01\ \mathrm{s}^{-1}$ shear. The predicted and measured widths agree very well for this experiment.

If the ice crystal fall rates were slower or if crystals did not fall from the top of the seeding curtain to the measurement level, the effects of shear would still be significant. If the plates were growing at $0.5\ \mu\mathrm{m\ s}^{-1}$ or if terminal velocities were better described by broad-branched crystals growing at $1\ \mu\mathrm{m\ s}^{-1}$, predicted widths would be of the order of half the measured widths. If particles were growing at $1\ \mu\mathrm{m\ s}^{-1}$ but were only produced 100 m above the measurement level, Fig. 3 illustrates that shear effects would again roughly account for half the measured widths.

4. Discussion

If the column is initially composed of ice nuclei in a cloud such as stratus and new ice crystals are being produced continuously, there should be some microphysical indications of the downwind spread of particles. The obvious effect should be an increase in ice crystal size from the upwind to the downwind sides of the column. Such a transition was measured in this seeding experiment. Another possible effect should be an asymmetry in ice particle concentration across the column. High concentrations of small particles should be present on the upwind edge of the column; low concentrations of large particles should be present on the downwind edge. Although not as distinct as the particle size results, such a general decrease in particle concentration was measured during this seeding experiment.

To confine this note to only the effects of particle terminal velocity is naturally a simplification of atmospheric conditions. We have shown here that in certain situations, such as in a stratus deck, terminal velocity effects in wind shear can account for much of the spread of columns. However, in other situations, such as in many convective clouds, turbulence and vertical air motion effects will undoubtedly be much more important to column widening than fallspeed contributions.

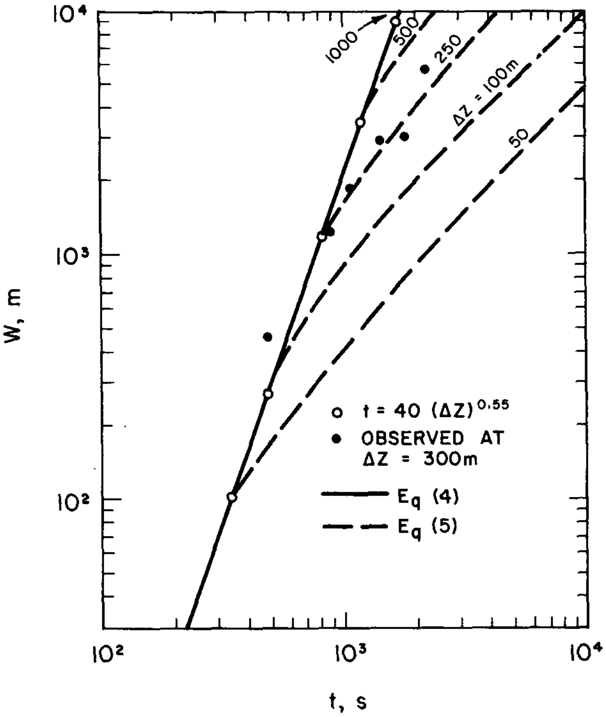

FIG. 3. Width (m) as a function of time and distance below column top for variable fallspeeds. Fallspeed of thin plates increases as the particles grow at $1\ \mu\mathrm{m\ s}^{-1}$, wind speed shear is $0.01\ \mathrm{s}^{-1}$ and new particles are assumed to be produced continuously. Adjusted observations from a seeding experiment ~300 m below column top are included.

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