MODEL SIMULATION OF SEEDING REPEAT RATES FOR DIRECT INJECTION SEEDING BY ROCKETS

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Abstract. A two-dimensional non-hydrostatic numerical convective cloud model is used for simulation of transport and diffusion of reagent in the conditions of direct injection seeding by rockets. Target area for the seeding is defined on the basis of model-produced radar reflectivity field. Reagent is released instantaneously along a line 1.5 km long, thus emulating rocket seeding. Results show that time of reagent residence in the target zone is less than two or three minutes. During this time, reagent spread from the plume axis did not exceed 50 m. Implication for the seeding repeat rate is that seeding by direct injection should be performed continuously while seeding criteria are satisfied. In practice this means that seeding repeat rate should be determined from the technical feasibility requirements.

1. INTRODUCTION

The amount of the reagent to be seeded and seeding repeat rates are among principal problems of operational hail suppression. So far, the values used in practice are determined solely on the basis of conceptual models, with all the quandaries this approach entails.

In this study, we have tried to approach the problem of seeding repeat rates in a more exact way by analyzing transport and diffusion of reagent in the numerical cloud model. Our primary goal was to follow the position of the reagent with regard to the target zone. Any mirophysical processes involving reagent particles would reduce reagent concentration, but would not reduce extent of its spread. Thus, we do not consider such processes, but treat reagent as a passive substance.

In the second part of this paper, we will describe basic model characteristics and the way we calculate trajectories and dispersion of the reagent. In the third part, we will describe the general history of the simulated cloud as well as transport and diffusion of the reagent. Finally, we will present our conclusion.

2. THE MODEL

2.1 General Model Characteristics

Only basic model characteristics will be stated here. More detailed information regarding hydrodynamical equations, turbulence closure and numerical methods used can be found in Klemp and Wilhelmson (1978). For thermodynamics and microphysical processes, Lin et al. (1983) is the source reference.

The current version of the model has ten prognostic equations: three momentum equations, thermodynamic and the pressure equation, four continuity equations for the water substance (mixing ratios of water vapor, cloud water, and cloud ice are treated by one equation), and turbulent kinetic energy equation. Thus, prognostic variables are mixing ratios of water vapor, cloud water, cloud ice, rain, snow, and graupel, three components of wind velocity, poential temperature, pressure, and the coefficient of turbulent diffusion.

Parameterization of the subgrid scale fluxes is based on the solution of the turbulent kinetic energy equation, with first-order closure applied to the nearly conservative variables. Heat eddy coefficient is assumed to be proportional to the momentum eddy coefficient.

Bulk water parameterizations are used for simulation of microphysical processes. Six classes of water substance are considered: water vapor, cloud water, cloud ice, rain, snow, and hail. Cloud water and cloud ice are assumed to be monodisperse, with zero terminal velocities. Rain, hail, and snow have the Marshall-Palmer type size distributions with fixed intercept parameters.

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These six forms of the water substance interact mutually. Condensation and deposition of water vapor produce, respectively, cloud water and cloud ice. Conversely, evaporation and sublimation of cloud water and cloud ice maintain saturation. Cloud ice is initiated by using a Fletcher type equation for the ice nuclei number concentration. It may also be produced by the Hallet-Mossop ice multiplication. The Bergeron-Findeisen process transforms some of the cloud water into the cloud ice and, to a certain extent, both of them into the snow. Rain is produced by autoconversion of the cloud water, melting of the snow and hail, and shedding during the wet growth of hail. Hail is produced by the autoconversion of the cloud water, melting of the snow and hail, and shedding during the wet growth of hail. Hail is produced by the autoconversion of snow, interaction of cloud ice and snow with rain, and by the immersion freezing of rain. Snow may be produced by the autoconversion and Bergeron-Findeisen growth of cloud ice and by the interaction of cloud ice and rain. All of the precipitation elements grow by different forms of accretion. Evaporation (sublimation) of all types of hydrometeors is also simulated.

Equivalent radar reflectivity factors for rain and hail are calculated after Smith *et al.* (1975), and for snow after Sekhon and Srivastava (1970). Because of integration over particle sizes to infinity, these factors are known to be too high. In our experience, when simulating hail producing clouds, the model tends to produce maximum reflectivities which are about 15 dBz too high compared to actually observed. To get more realistic values from all calculated reflectivity factors, we arbitrarily subtract 15 dBz.

Model equations are solved on a semi-staggered (C) grid. All scalar variables are block centered, while the velocity components are node centered. The horizontal and vertical advection terms are calculated, respectively, by the centered fourth- and second-order differences. Since the model equations are compressible, a time splitting procedure is applied with a second-order leapfrog scheme used for the portions of calculations which do not involve sound waves. A forward-backward time differencing scheme is used for the acoustic part of the equation.

Boundary conditions are defined so that the normal component of the velocity is assumed to vanish along the bottom and top boundaries. The normal mixing terms are set to be zero at the top, bottom, and lateral boundaries. The lateral boundaries are open and time-dependent so that disturbances can pass through with minimal reflection. Two different cases with regard to the wind velocity are considered, after Durran (1981). When the component of velocity normal to the boundary is directed toward the domain (inflow boundary), normal derivatives are set to be zero. At the outflow boundaries, for all variables except pressure, normal derivatives are calculated by the upstream differences, with a time lag of a large time step in order to ensure stability. Pressure boundary conditions are calculated from other boundary values to maintain consistency.

Simulations present in this paper are obtained by a two-dimensional version of the model. Integration domain is 34 km in the horizontal and 12 km in the vertical direction. Grid step is 1 km in the horizontal and 0.5 km in the vertical direction. The large time step is 10 s, and the small time step is 2 s.

2.2 Calculation of the Reagent Trajectory and Diffusion

When seeded by rockets, the reagent is normally released as a practically instantaneous line source, seeding path having the length of the order of 1 km. The initial spread of the agent might be some 10 m. Obviously, reagent is released on the subgrid scale with respect to our cloud model.

In order to treat advection and diffusion explicitly, we have used the Lagrangian approach. The line of the released reagent is approximated by a series of individual spherical puffs with the 10 m radius. Puff trajectories are calculated from the wind speed bilinearly interpolated from the four nearest grid points. Turbulent spread of the reagent in the individual puff is described by the increase of its radius, which is a function of the coefficient of turbulent diffusion (Georgopoulos and Seinfeld, 1986)

$$\sigma_{i+1}^2 = \sigma_i^2 + 2K\Delta t$$

Here, σ_{i+1} is the puff radius in the time step $i+1$, σ_i is the puff radius in the preceding time step and Δt is the time step. K is the value of the turbulent diffusion coefficient on the puff center position; it is bilinearly interpolated from the known values of four nearest grid points. This approach is valid as long as the puff size does not exceed grid cell size, a condition satisfied for our experiment.

3. NUMERICAL EXPERIMENT

The model is initialized on the Belgrade sounding for 24 June 1973, 1300 local time (Fig. 1). Initial impulse for the convection is an ellipsoidal thermal bubble centered 6 km to the left of the domain middle at the height of 1500 m. Horizontal bubble radius is 10.8 km and vertical is 1 km. Temperature perturbation is maximal in the bubble center (+4°C) and exponentially decreases towards zero on the bubble boundary.

3.1 General Model Cloud Appearance

The model cloud forms as a Cu hum 6.5 min after the initialization and rapidly develops, so that

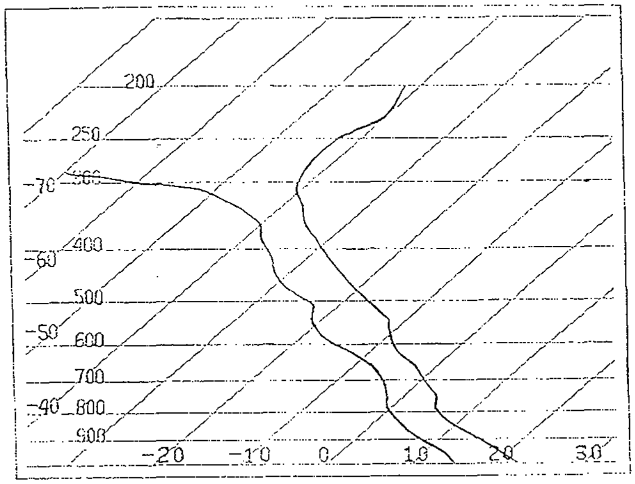

Figure 1: Atmospheric sounding for Belgrade, 24 June 1973, 1300 LST.

traces of the cloud ice occur in 10 min. Figure 2 shows a sequence of general cloud appearance in 12, 16, 20, 24, 28, and 32 min. On these figures, arrows show wind field, and full line contour delineates area with non-precipitating cloud elements; it should be interpreted as a cloud contour. Stars, dots, and symbols 's' show the places with the concentrations, respectively, of the hail, rain, and snow exceeding 1 g kg^{-1}.

By 12 min, the cloud could be described as a Cu med, and 1 min later raindrops occur. Hail occurs in the 15th min, and the snow in the 16th, when the cloud is Cu cong and has depth of 6.5 km.

In the 19th min of simulation, updraft speed has reached its maximum of 17.2 m s^{-1}. About this time, hydrometeor growth intensifies so that in the 23rd min hail reaches a maximum concentration of 6.9 g kg^{-1}. The cloud picture in the 24th min shows Cb calv about 9 km deep. Fallout of hail induces melting and the concentration of rain increases to its maximum value of 6.3 g kg^{-1} in the 27th min.

The fallout of hydrometeors weakens the updraft intensity and cuts off the supply of the water vapor from the surface, so that the cloud enters its dissipation phase around the 25th min. General cloud appearance in the 28th min clearly shows weakened surface convergence. Because of the weakened updraft, the cloud top spreads horizontally to form a characteristic anvil; we can now identify the cloud as a Cb in. In the 32nd min, there is practically no updraft near the cloud base and, except for snow in the anvil area, there are no significant concentrations of hydrometeors. In the 36th min (not shown on the figure), only fragmented structures of the decayed cloud remained. At this point, maximum of accumulated rain was 36 mm, and of hail 6 mm. As a summary, simulation produced a moderate single cell hailstorm.

3.2 Reagent Dispersion

When releasing agent in the model cloud, we have tried to be as close as possible to the seeding procedures of the Serbian hail suppression system, as described by Aleksic (1989). This way, the reagent is seeded in the 20th min in the layer (-6°C, -12°C) between the equivalent radar reflectivity contours of 25 and 45 dBz, at the height of 5000 m. The seeding line is 1.5 km and represented by 16 initially equidistant puffs with 10 m radii.

The time sequence of the reagent position is shown in Fig. 3. In this figure, a full line marks the cloud outline, while quasihorizontal dashed lines show the position of -6°C and -12°C isotherms. Curved dashed lines are 25 dBz and 45 dBz equivalent radar reflectivity contours. Puff positions are marked by small circles. It should be noted that, in order to improve visibility, circle sizes are exaggerated, though proportional, to the puff sizes.

In the simulated cloud, as shown in Fig. 2, a strong updraft swiftly carries the reagent out of the target zone. One minute after the release, most of the material is above the -12°C isotherm. As can be seen, after several minutes, part of this material is recirculated downward along the cloud edge, but there is no ground for any generalization.

Growth of individual puffs is very limited. After 5 min, puff radii are still below 50 m. In effect, line of reagent moves through the cloud in the form of a rope, a feature usually observed in airborne measurements of tracer transport in convective clouds (Warburton *et al.,* 1986). The low spread of the agent is somewhat surprising, but agrees well with the order of magnitude calculations based on the characteristic values of turbulent energy dissipation rates (WMO, 1980).

4. DISCUSSION

The numerical experiment described above shows that advection of the reagent is very intensive and its diffusion very limited. Reagent is released in the updraft (as it is supposed by the methodology), and because of this, its residence time in the target zone [in the (-6°C, -12°C) layer, between the 25 dBz and 45 dBz contours] is very short, not exceeding 2 to 3 min.

Thus, if we choose to satisfy the methodological requirement that the target zone should contain seeding material when the seeding criteria are met, direct injection seeding by the rockets should be performed almost continuously and, in any case, in intervals not exceeding a few minutes. From the practical point of view, this implies very high rocket expenditure and raises the question of whether it would be more economical to switch to some other delivery technique, like aircraft seeding.

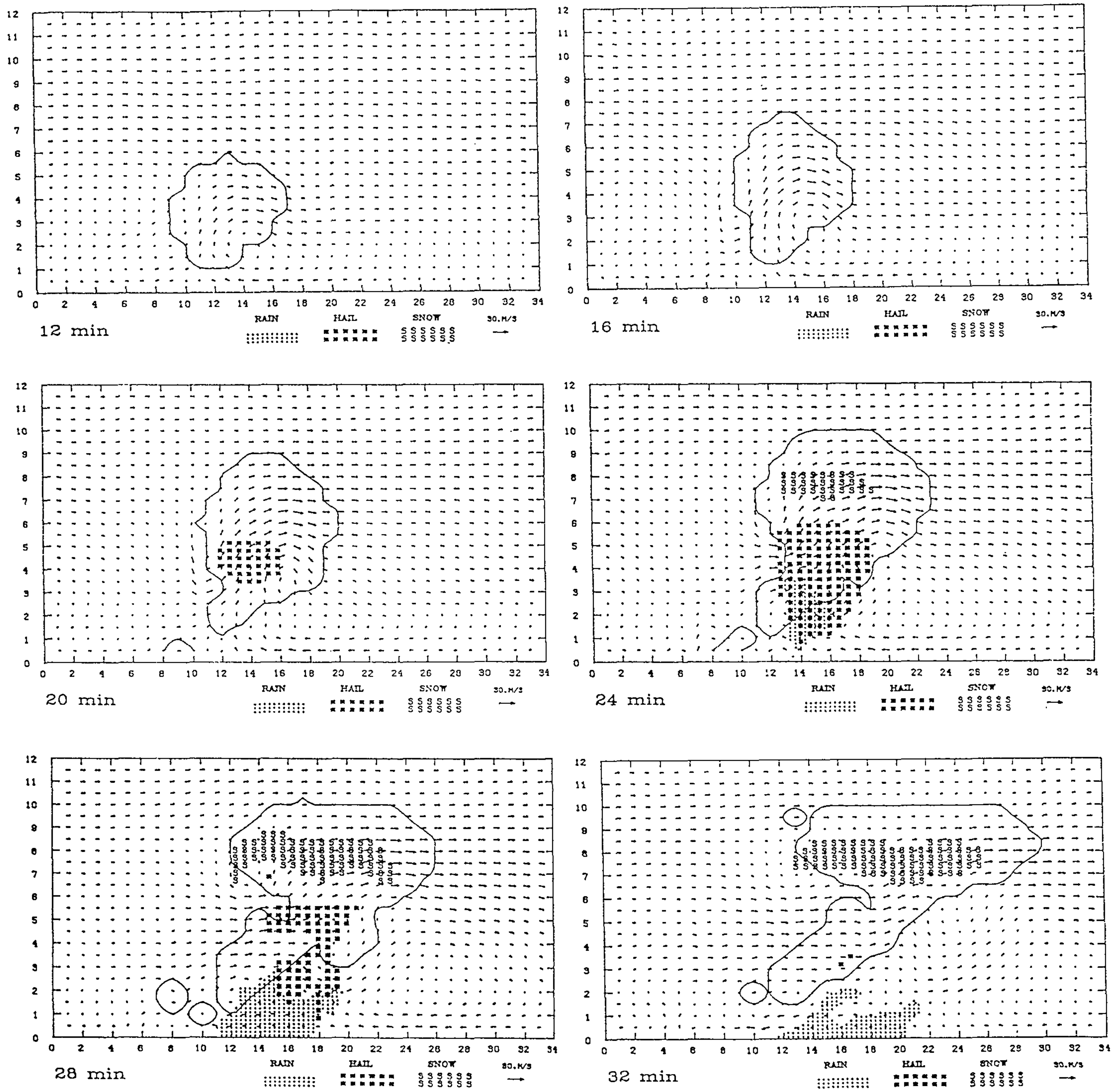

Figure 2: General cloud history. Arrows denote wind, full contour cloud outline, and asterisks, dots, and s-es presence of hail, rain, and snow in concentrations greater than 1 g kg^{-1}.

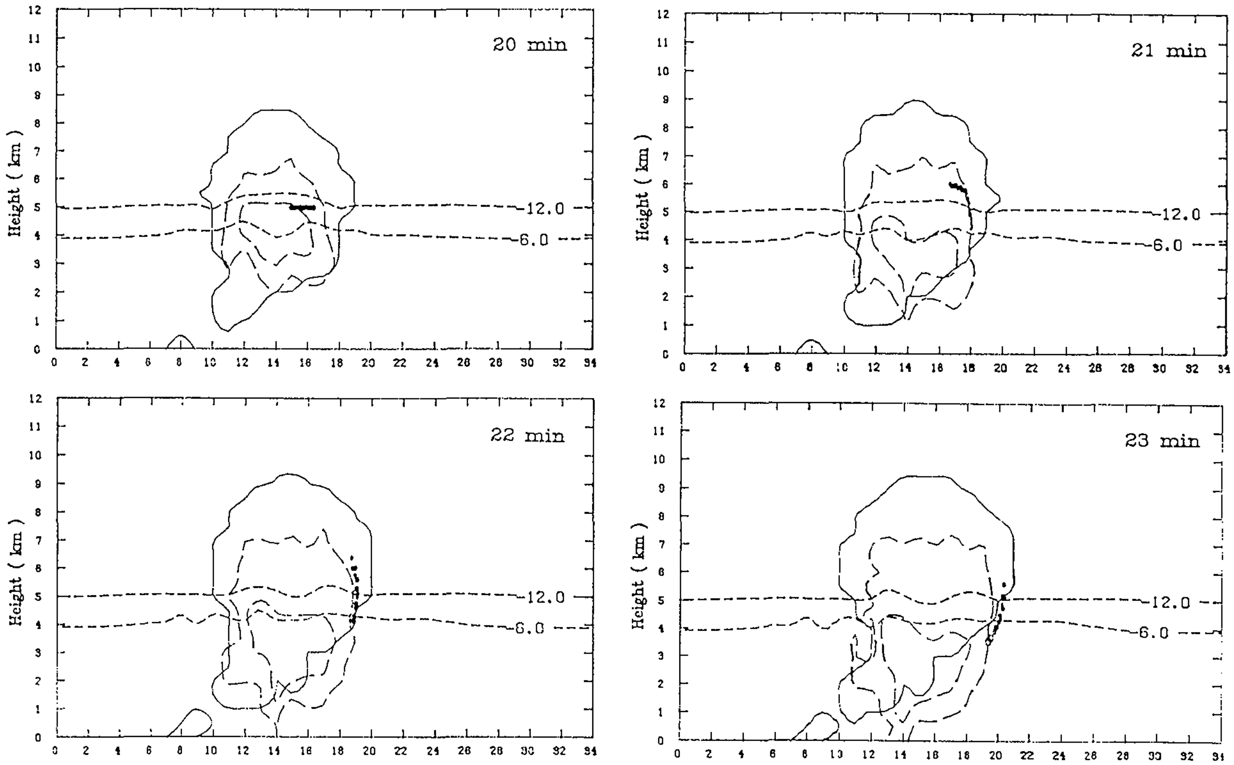

Figure 3: Spread of reagent. Full line marks the cloud outline, while quasi-horizontal dashed lines show position of -6°C and -12°C isotherms. Curved dashed lines are 25 dBz and 45 dBz equivalent radar reflectivity contours. Puff positions are marked by small circles (exaggerated in size).

The surprisingly low spread of the agent we observed in the model has very serious bearings on the methodology of seeding by rockets, which is based on the assumption that the agent spreads throughout the target zone. Low spread implies that there are small overseeded pockets, while most of the target zone is not affected at all by the seeding. This methodological quandary obviously requires a serious deliberation.

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