ON THE CONSUMPTION OF AgI SEEDING AGENT: DEPENDENCE ON THE LIQUID WATER CONTENT IN THE SEEDING ZONE

Mladjen Ćurić and Dejan Janc
Institute of Meteorology, University of Belgrade, Belgrade, Serbia, Yugoslavia

Abstract. A one-dimensional kinematic model of Lagrangian type is applied to investigate some hail suppression efficiency parameters dependence on the liquid water mixing ratio in the seeding zone. The silver iodide seeding agents are injected at the bottom of the seeding zone (a level of -8°C). Their interaction with cloud is simulated by a microphysical model. It calculates the maximum seeding agent mixing ratio at the bottom of the seeding zone needed to produce the critical number concentration of graupel at its top. This ratio is expressed through the number of hail rockets fired (N). The value of N strongly depends on the type of agent especially for lower values of liquid water mixing ratio.

1. INTRODUCTION

Extensive field measurements and numerical modeling efforts have been made during the last three decades to examine the physical and dynamic processes taking place in hailstorms and also to develop the reliable hail suppression technology. One of the concepts for reducing the sizes and concentrations of hailstones falling from convective storms is beneficial competition (Sulakvelidze, 1967). Many hail suppression projects all over the world have been organized (Federer, 1977; Miller and Fuchs, 1987). One of them is the operational hail suppression project based on the beneficial competition concept which has been in operation in Serbia twenty-seven years, where the hail suppression system covers about 40,000 km^2 of agricultural surface. This is one of the largest areas in the world protected by such a system (Ćurić, 1990; Radinović, 1972). Now, it will be expanded by an additional 20,000 km^2 in the agricultural area of Vojvodina. The hail suppression technology used is that of injecting the silver iodide by rockets into the zone between isotherm levels of -8°C and -12°C, when the radar reflectivity is greater than 25 dBz.

Measuring technology has increased the amount and quality of data available from hail suppression programs. Nevertheless, improvement of the measurements to the required degree is likely to be slow because of the technical difficulty of obtaining data which are at once comprehensive, accurate, representative and without temporal and spatial limitations. Numerical modeling offers the opportunity to supplement the measurements. It may be possible to obtain useful insight into the cloud seeding zone by studying it through numerical modeling (Ćurić and Janc, 1990; 1993; Farley *et al.*, 1994 a,b).

The choice of seeding material and its efficiency when it is injected into the cloud has not been subjected to rigorous examination until now, largely due to the lack of quantitative knowledge of the dynamical and microphysical characteristics of the atmosphere in the seeding zone. This paper will attempt to examine the dependence of seeding agent's residence time in the seeding zone and the final graupel production at its top upon the liquid water mixing ratio inside it. A 1-D kinematic model will be used to access the utility of seeding material used.

2. MODEL DESCRIPTION

A 1-D kinematic model of Lagrangian type (Ćurić and Janc, 1993) is applied to investigate the seeding agent's residence time and the final graupel production in the seeding zone. It is assumed that the vertical velocity depends on the graupel production resulting from seeding.

The number concentration of the produced graupel is calculated by microphysical model described by Ćurić and Janc (1990, 1993). The microphysical scheme of the model is shown in Ćurić and Janc (1990). The seeding agent may produce cloud ice by several mechanisms. Among them, the contact and deposition nucleation mechanisms are the most important.

The main assumptions for the model parameters inside the seeding zone are as follows. The lapse rate of temperature is taken to be

7 K km^{-1}. The mean climatological value at the base of the seeding zone is 570 hPa. The depth of the seeding zone in all calculations is 571 m. The liquid water content is assumed to be fixed; we use the liquid water mixing ratio of 3, 4 and 5 x 10^{-3} kg kg^{-1} in our calculations. The Khrgian-Mazin size distribution for the all drop spectrum is assumed. The mean droplet radius takes the value of 60 μm. The value of the reference vertical velocity is taken to be fixed (in our case 20 ms^{-1}). The entrainment rate, μ, is given the fixed value of 10^{-3} s^{-1}.

In the operative Hail Suppression Project in Serbia, four principal types of agents are applied (TG-10, TG-5, SAKO-6 and PP-6). Their maximum values of the seeding agent mixing ratio and particle masses are presented in Ćurić and Janc (1993). They are based on the results of Hsie *et al.* (1980). The modal radius of the seeding agent size distribution is supposed to be $R_g = 0.03$ μm.

The continuity equation for the silver iodide mixing ratio is the same as in Ćurić and Janc (1993), except that the immersion freezing term is omitted. So, the main sink terms are caused by the turbulent diffusion process (described over the entrainment rate) as well as the Brownian and inertial collection rates due to cloud droplets and raindrops, phoretic processes, and deposition nucleation. The analyzed mixing ratio is related to the maximum seeding agent mixing ratio.

3. MODEL RESULTS

In order to investigate the effectivity of each particular seeding agent in producing graupel, the final graupel production(N_{gf}) as a function of the liquid water mixing ratio is presented in Fig. 1. This production is a result of the aerosols released per m^3 from one rocket fired at the bottom of the seeding zone. It is clearly shown that the PP-6 and the SAKO-6 aerosols are much more effective in producing graupel compared to the TG-10 and TG-5 aerosols. Also, the slopes of curves for PP-6 and SAKO-6 are larger than for the other two agents. For the TG-10 agent this production is practically independent of liquid water mixing ratio.

The time evolution of different microphysical mechanisms responsible for final graupel production is shown in Fig. 2 for a liquid water mixing ratio of 3 x 10^{-3} kg kg^{-1}.

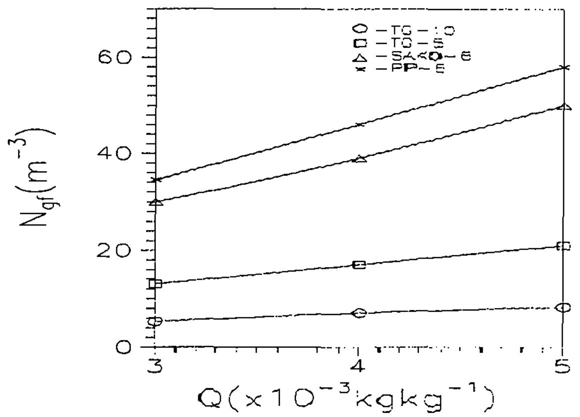

Fig. 1: The final graupel production, $N_{gf}(m^{-3})$, as a function of the liquid water mixing ratio, $Q(x10^{-3}$ kg kg$^{-1})$, for four types of the seeding agents.

The rates of change in number concentration of cloud ice or graupel particles are designated by J_x. The subscript x takes values: bc, ic, br and ir for the Brownian and inertial collection rates due to the cloud droplets and raindrops, while rcn and rd are related to accretion rates caused by collecting the cloud ice generated by contact and deposition nucleation mechanisms, respectively, by raindrops.

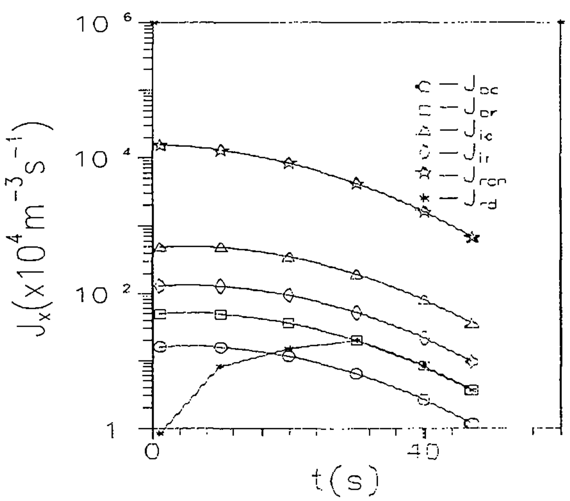

Fig. 2: The rate of change in number concentration, $J_x(\times 10^4 m^{-3}s^{-1})$, caused by: Brownian and inertial collection rates due to cloud droplets and raindrops $(J_{bc}, J_{ic}, J_{br}, J_{ir})$, accretion rates between cloud ice formed by contact or deposition nucleation and raindrops (J_{rcn}, J_{rd}), as a function of time for the PP-6 aerosol and $Q = 3 \times 10^{-3}$ kg kg^{-1}.

All mechanisms except J_{rd} decrease with time. The greatest values are for contact nucleation (J_{rcn}). The mechanisms analyzed provide higher values for a fixed time as the liquid water content increases.

The values of terms J_x at any time depend on the number concentration of droplets and raindrops. In order to illustrate the dependence of values of J_x on the liquid water mixing ratio (Q), the initial cloud droplet, $N_c(m^{-3})$, and raindrop, $N_r(m^{-3})$, number concentrations as functions of Q are shown in Table 1. It can be seen that both N_c and N_r increase with liquid water content.

Table 1. The initial cloud droplet, $N_c(m^{-3})$, and raindrop, $N_r(m^{-3})$, number concentrations, as functions of the liquid water mixing ratio, $Q(x10^{-3}$ kg kg$^{-1})$, for $R_M = 60\,\mu m$.

	$Q(x10^{-3}$ kg kg$^{-1})$		
	3	4	5
$N_c(m^{-3})$	$5x10^5$	$7x10^5$	$8x10^5$
$N_r(m^{-3})$	$6x10^5$	$8x10^5$	10^6

The aerosol residence time (t_R) as a function of the liquid water mixing ratio for four seeding agents used is shown in Table 2. It may be observed that values of the residence time for Q = 3 x 10^{-3} kg kg^{-1} differ more significantly than those for Q = 5 x 10^{-3} kg kg^{-1}. The residence time as well as the final graupel production are the greatest for PP-6.

Table 2. The agent residence time $t_R(s)$, as a function of the liquid water mixing ratio, $Q(x10^{-3}$ kg kg$^{-1})$, for four agents used under condition when $w = 20$ ms^{-1}, $\mu = 10^{-3} s^{-1}$, and $R_M = 60\,\mu m$.

	$Q(x10^{-3}$ kg kg$^{-1})$		
	3	4	5
	$t_R(s)$	$t_R(s)$	$t_R(s)$
TG-10	110	103	102
TG-5	96	124	89
SAKO-6	94	80	115
PP-6	122	97	161

The primary parameter in an operational hail suppression project is the maximum seeding agent mixing ratio at the bottom of the seeding zone needed to generate the critical number concentration of graupel (100 m^{-3}) at its top (Srivastava, 1967). It can be expressed through the number of hail rockets fired (N).

The relationship between the number of rockets (N) and liquid water mixing ratio (Q) is illustrated in Fig. 3. It is seen in this figure that rockets with PP-6 and SAKO-6 chemical formulations follow the same trend. N is nearly independent of Q for the aerosols produced by these two types of rocket compositions. For the other two agents this interdependence is stronger, especially for TG-10. The number of rockets N is always greater for TG-10 in comparison to those for PP-6 and SAKO-6, especially for smaller values of Q.

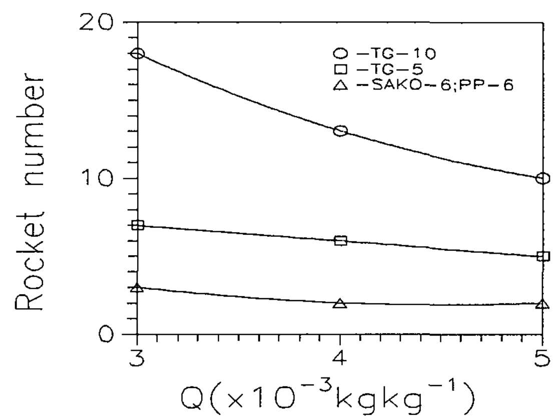

Fig. 3: The number of rockets required for four agent types as a function of the liquid water mixing ratio (Q).

By comparing the differences in N for each four aerosols it is obvious that the number of rockets fired in order to produce the critical number concentration of graupel strongly depends on the type of seeding materials which they contained. For lower values of liquid water mixing ratio, this difference becomes a factor of six. Because the price of one rocket is practically independent of the seeding agent, the cost of hail suppression can be significantly reduced by using the most efficient graupel producing seeding agent, especially for lower liquid water mixing ratios in the seeding zone.

4. CONCLUSIONS

Results presented in this paper show that the seeding agent residence time in the seeding zone, the final graupel production at the top of the seeding zone, and the number of hail rockets fired (N) needed to produce the critical number concentration of graupel strongly depends on the values of the liquid water mixing ratio in the seeding zone, especially for the TG-10 seeding agent.

It has been found that consumption of hail rockets (N) can be six times smaller for lower liquid water mixing ratio clouds if it is a PP-6 or SAKO-6, instead of a TG-10. This means that the cost of hail suppression can be significantly reduced by using the appropriate seeding agent, especially for clouds with lower liquid water mixing ratios.

These types of numerical calculations improve our understanding of hail suppression activity based on the beneficial competition concept.

Acknowledgments. This research is partly supported by the Union of Science of Serbia.

REFERENCES

Ćurić, M., 1990: One evidence of the hail suppression efficiency derived from radar measurements. *J. Wea. Mod.*, **22**, 79-81.

Ćurić, M., and D. Janc, 1990: Numerical study of the cloud seeding effects. *Meteorol. Atmos. Phys.*, **42**, 145-164.

Ćurić, M., and D. Janc, 1993: Dependence of the simulated seeding effects of Cb cloud on the types of the AgI agents. *Meteorol. Atmos. Phys.*, **52**, 91-100.

Farley, R. D., P. Nguyen, and H. D. Orville, 1994a: Numerical simulation of cloud seeding using a three-dimensional cloud model. *J. Wea. Mod.*, **26**, 113-124.

Farley, R. D., T. Wu, H. D. Orville, and H. Chen, 1994b: The numerical simulation of hail suppression experiments. *Proc. Sixth WMO Sci. Conf. on Wea. Mod. WMO WMP*, **22**, 161-166.

Federer, B., 1977: Methods and results of hail suppression in Europe and in the USSR. *Meteor. Monogr.*, **38**, 215-223.

Hsie, E.-Y. , R. D. Farley, and H. D. Orville, 1980: Numerical simulation of ice-phase convective cloud seeding. *J. Appl. Meteor.*, **19**, 950-977.

Miller, J. R., and M. J. Fuchs, 1987: Results of hail suppression efforts in North Dakota as shown by crop hail insurance data. *J. Wea. Mod.*, **19**, 45-49.

Radinović, D. J., 1972: *Hail Control.* 124 pp. (NTIS, Springfield, VA 22151).

Sulakvelidze, G. K., 1967: Showers and hail. [In Russian] Leningrad, Gidrometeoizdat. 412 pp.