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NUMERICAL SIMULATION OF PRECIPITATION ENHANCEMENT IN STRATIFORM CLOUD

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1. INTRODUCTION

Stratiform clouds associated with synoptic disturbance are the important source of precipitation in northern China. They are also the objects of precipitation enhancement experiments. Observation of You (1980) showed that the ice concentrations in these clouds usually are very high and the supercooled water contents are low. According to the closed model of ice-water conversion, the potential of precipitation enhancement by cloud seeding is limited. However, the experiments of Leskov (1973) in USSR showed significant value of precipitation enhancement, which was much larger than the sum of supercooled water in cloud at the given moment. Evaluation of the precipitation enhancement potential in stratiform clouds remains a crucial problem in the design of a cloud seeding experiment. The potential of rain enhancement from warm stratiform clouds by salt seeding is also an interesting and important subject.

2. MODEL

The mechanisms and potential of cloud seeding in stratiform clouds are examined in this paper by a one-dimensional time-dependent model of Hu (1984). The evolution of water vapor (Q_v), cloud water (Q_c), water content and number concentration of raindrops (Q_r, N_r), ice crystals (Q_I, N_I), snow aggregates (Q_s, N_s) and graupel (Q_g, N_g) are predicted with consideration of advection, turbulent mixing, fallout and 19 microphysical processes which include the condensation, sublimation, collection, aggregation, riming, ice nucleation, ice multiplication (Hallett-Mossop process), autoconversions of cloud to rain, ice to graupel, snow to graupel, evaporation and melting. The model is verified in six cases. The calculated microstructures are coincident with observations of many aspects.

In this paper the updraft in cloud is assumed to be

$$W(Z)=W_m\,[1-(2\cdot Z/H-1)^2]$$

where W_m is the maximum updraft velocity, H is the depth of cloud. The temperature profile is assumed to be wet adiabatic. Turbulent mixing coefficient $K=20m^2/s$. Initially the air is saturated with respect to ice and no hydrometeors exist.

3. CONTINUOUS AGI SEEDING

Ice nucleation rate is assumed to be 9 times larger than in the natural case to simulate the continuous AgI seeding.

3.1 Development of natural and seeded cloud

The total concentration of precipitation particles $N_p=N_i+N_s+N_g+N_r$, precipitation rate $\rho Q_p V_p=\rho(Q_I V_i + Q_s V_s+Q_g V_g+Q_r V_r)$, cloud water Q_c and vapor excess over ice-saturation Q_v-Qsi in clouds with base temperature $T_b=0^oC$, top temperature $T_h=-27^oC$, H=3.6km, W_m= 0.2m/s are shown in Figure 1. The evolution of precipitation rate at cloud base is shown in Figure 2. At the beginning cloud water develops quickly. Ice particles are nucleated mainly in the upper part of cloud. Some of them grow and fall as graupel which produce the secondary ice in the lower part of the cloud. The first peak of precipitation appears at this time. When the main ice crystals develop and fall, the cloud water decreases sharply and the H-M process weakens. After 360 minutes the microstructure of cloud and precipitation becomes stationary. Here we note N_p, ρQV are larger and Q_c, Q_v are less in seeded case. The precipitation rate from a seeded cloud is 16% larger. It seems that the seeding potential is significant in this cloud, where the natural ice is abundant ($N_i=5/L$) and the supercooled water is small ($Q_c \leqslant 0.05g/kg$). The source of artificial precipitation seems to be the conversion of vapor to ice, as well as that of water to ice.

3.2 Seeding potential in clouds with various top temperatures.

The calculated precipitation rate in the stationary stage (I), its seeding increase (ΔI), the average precipitation rate in the initial 6 or 8 hours ($\bar{I}$) and its seeding increase ($\Delta\bar{I}$) are shown in Table 1, in which $T_b=0^oC$, H=2.4 to 4.0km, $T_n=-16$ to -30^oC. The calculated profiles of N_p, ρ QV, Q_c, Q_v-Qsi in stationary stage are shown in Figure 3. The seeding effect is most significant at $T_h=-21^oC$, where ΔI=25%. It agrees with the concept of "temperature seeding window". The major source of artificial precipitation in this case is the conversation of cloud water to ice, as $\Delta Q_c >> \Delta Q_v$. In the case of $T_n=-16^oC$, the artificial ice particles are too limited to

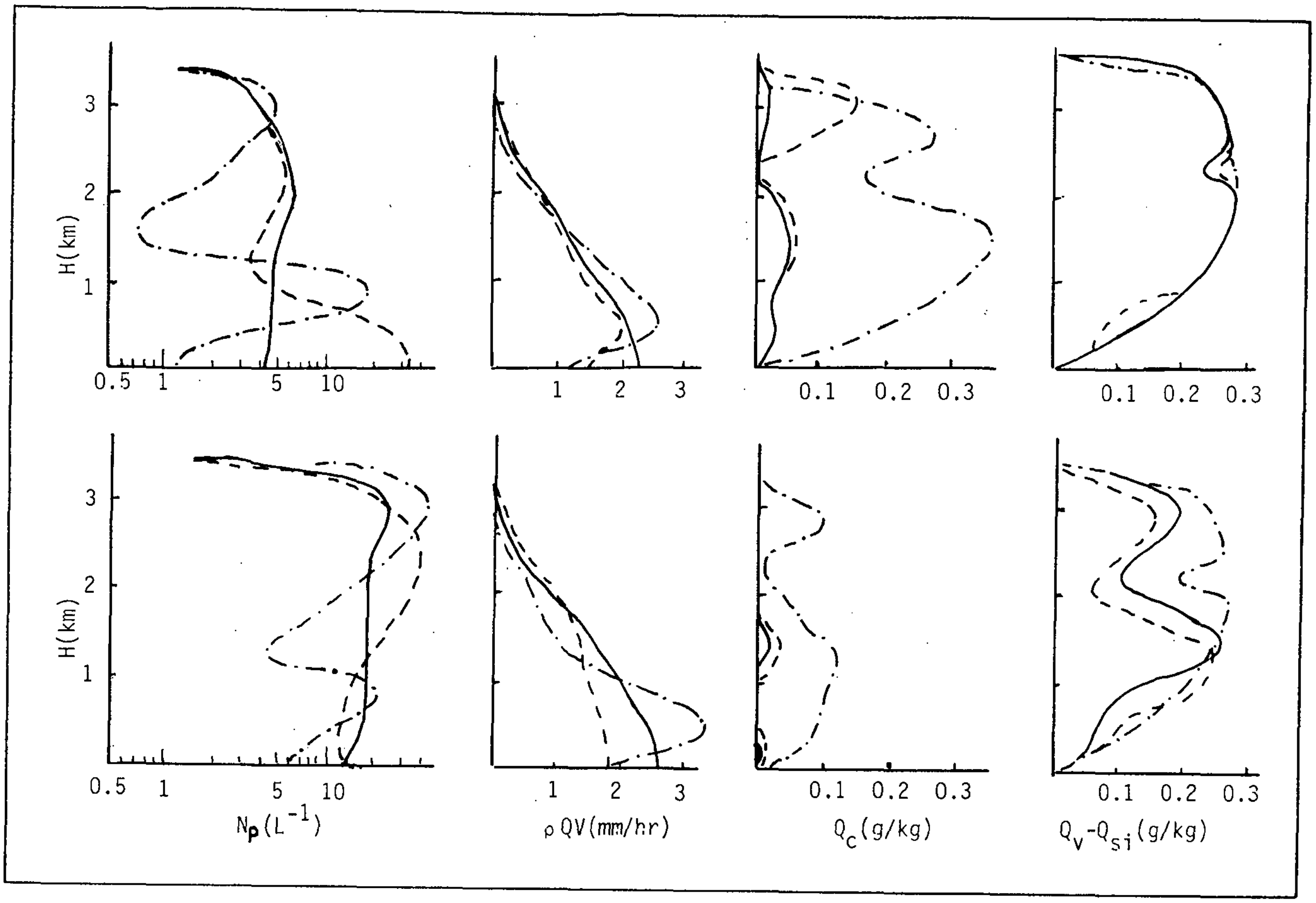

Figure 1. Evolution of the Profiles of Nρ, ρQV, Q_c, and Q_v-Q_{si} in Natural (upper) and Seeded (lower): —·—·— 60 min. – – – 120 min. ——— 360 min.

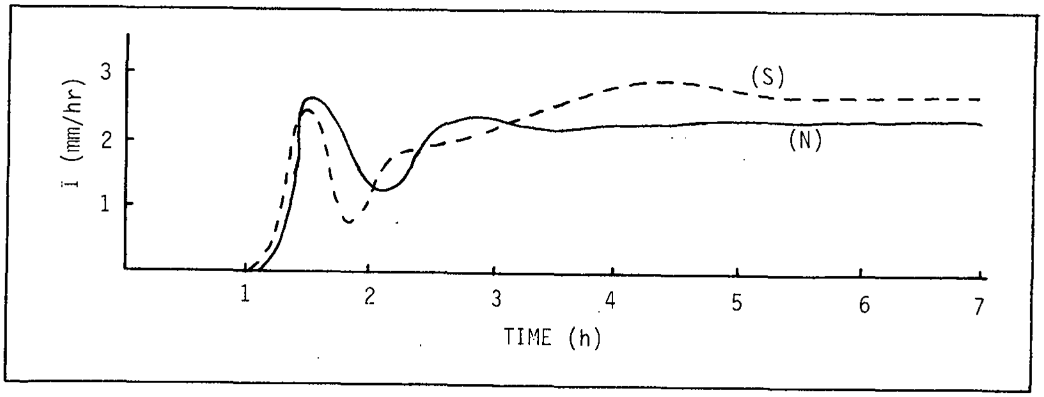

Figure 2. Evolution of Precipitation Rates at Cloud Base for Natural (N) and AgI Seeded (S)

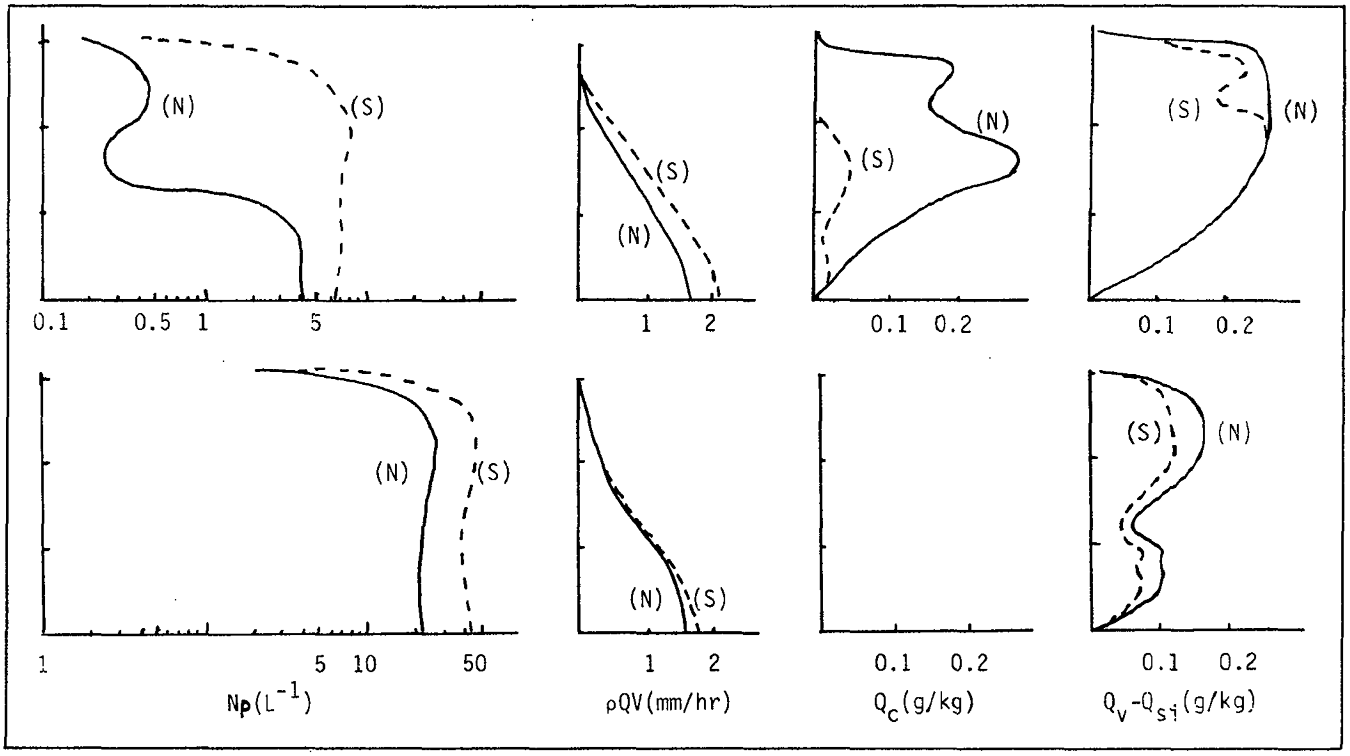

Figure 3. Profiles of Np, ρQV, Q_c, and Q_v-Q_{si} in stationary stag in Natural (N) and Seeded (S) Clouds with T_h = -21^oC (upper) and T_h = -30^oC (lower)

Table 1. AgI Seeding Effects Under Different Conditions

H km	2.4	3.0	3.6	4.0	3.0	3.0	3.0
T_h ^oC	-17	-21	-27	-30	-21	-21	-21
W_m m/s	0.2	0.2	0.2	0.2	0.1	0.2	0.4
I mm/hr	1.47	1.74	2.32	2.80	0.83	1.74	3.79
I %	5	25	16	4	16	25	40
$\bar{I}$ mm/hr	1.30	1.55	1.95	2.20	0.70	1.55	4.10
$\bar{I}$ %	2	12	11	7	10	12	17

Table 2. Evolution of ρQV, Qρ, and Vρ at Cloud Base in Dry Ice Seeded Cloud

Time (min)	ρQV (mm/hr)	Qρ (g/kg)	$N_{\rho 1}$ (L^{-1})	Vρ (m/s)	Form
180	1.78	0.28	4.6	1.9	graupel
240	1.07	0.39	8.9	0.7	ice
360	4.46	1.21	8.1	0.9	snow
400	1.57	0.21	2.2	2.0	graupel
540	1.74	0.27	4.3	1.9	graupel

obtain a large seeding effect. In the case of T_h=-30°C the natural ice particles reach a value of 10/L and the supercooled water is very small. Cloud seeding under these conditions increases some percent of the precipitation (ΔI=4%, $\Delta\bar{I}$=7%), the source of which is mainly the conversion of vapor to ice, caused by enhanced sublimation.

3.3 Hallett-Mossop ice multiplication process

The H-M process plays a significant role in clouds with $T_h \geqslant -21°C$, where N_p reaches 4/L. In the region of T>-8°C in natural cloud, it may decrease the seeding potential. In clouds with $T_h \leqslant -27°C$, a large amount of ice is nucleated, the cloud water is small and the role of H-M process is limited.

3.4 Seeding potential in clouds with various updraft velocities

Calculations show that in clouds with T_h= -21°C the natural precipitation rate (I), cloud water (Q_c) and seeding potential (ΔI) increase with an increase of the updraft (W_m). (see Tab. 1).

4. TEMPORARY SEEDING WITH DRY ICE

A temporary increase of ice concentration (ΔN_i=3.10^5/kg) at 180 min in 150m thick layer of the upper cloud part is assumed to simulate the airborne dry-ice seeding in a rate of about 50g/km^2. The artificial ice crystals grow, diffuse and fall. The water content of ice particles ($Q_p = Q_i+Q_s+Q_g$) increases rapidly after seeding, while their average fall speed (V_p) decreased (see Tab. 2). The precipitation rate at cloud base (I_p) decreases for a short time, then increases (see Fig. 4.). In case of T_h=-21°C, I_p reaches a maximum value of 4.46 mm/h, which is 252% of the natural case. At 400 min, when the artificial ice particles fall out, I_p reaches a minimum value (90% of the natural). Then the I_p and cloud water return slowly to normal. The total precipitation at cloud base before 540 min. is 16.2mm, which is 12% more than in the natural case.

5. SALT SEEDING IN WARM CLOUD

5.1 Model

The mass content and number concentration of salt solution drops are calculated with other variables of equations:

$$\frac{\partial Q_h}{\partial t} = -W\frac{\partial Q_h}{\partial Z} + K\frac{\partial^2 Q_h}{\partial Z^2} + \frac{\partial Q_h V_h}{\partial Z} + \frac{Q_h}{Dt}\,\cdot$$

$$\cdot\ \left([(R_h^5 + B\cdot R_{ho}^{\ 3}\cdot F\cdot Dt)^{1/5} + 1/4E_h V_h \rho Q_c\cdot Dt]^3/R_h^3 - 1\right)$$

$$\frac{\partial N_h}{\partial t} = -W\frac{\partial N_h}{\partial Z} + K\frac{\partial^2 N_h}{\partial Z^2} + \frac{\partial N_h V_h}{\partial Z}\,.$$

where $B=5.i.\ M_w/M_h\cdot \rho_h\cdot K_d\cdot\rho\ \cdot Q_{sw}/[1+L\cdot K_d\cdot\rho\cdot Q_{sw}/K_t/T.(L/R/T-1)]$; radius of salt-solution drops $R_h = (3/4\cdot Q_h/\pi/N_h)^{1/3}$ ventilation factor (F_h), collision efficiency (E_h) and fall speed (V_h) are functions of R_h. At time t-t', in cloud layer of $H_1 \leqslant Z \leqslant H_2$, $Q_h=Q_{ho}$, $N_h=N_{ho}$, $R_h=R_{ho}$ are assumed to simulate the airborne salt seeding.

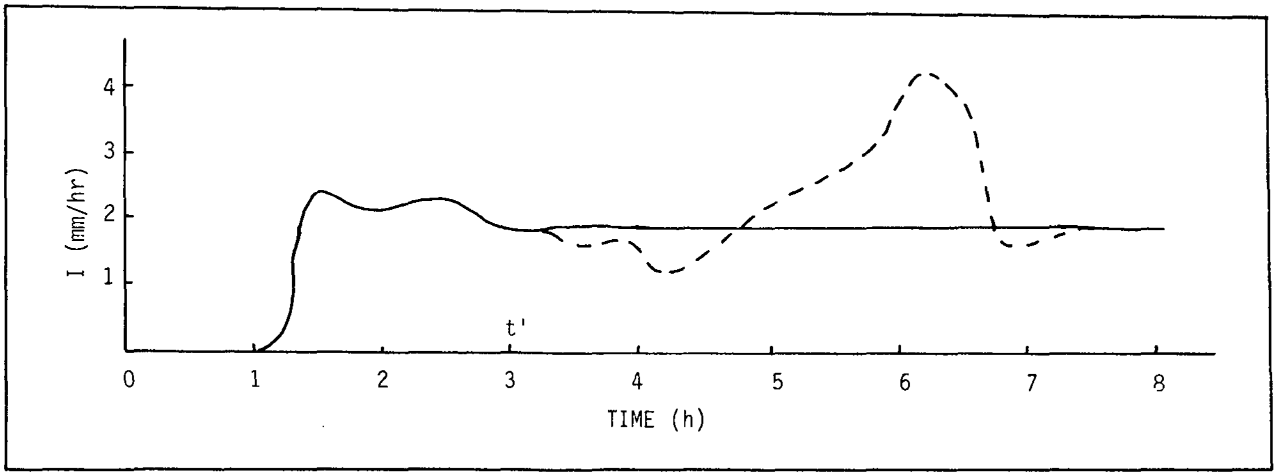

Figure 4. Evolution of Precipitation Rate at Cloud Base in Dry Ice Seeding Case

5.2 Results

The evolution of precipitation rate (I_p) is shown in Fig. 5 for natural and seeded cases in a cloud, where H=2.7 km, W_m=0.2m/s, T_b=15^{o}C, t'=60min, H_1=2.2 km, H_2=2.6km, $Q_{ho}=10^{-4}$g/kg, $N_{ho}=10^5$/kg. Salt particles grow, diffuse and fall out. After an hour there is a peak in precipitation rate, which continues about 20 minutes and the rainfall amount increases about 70% in this short period. Precipitation and cloud water become less than the natural case, after the salt solution drops fall out than return slowly to their natural stationary values. The total rainfall amount in 200 minutes increases only 3% by cloud seeding.

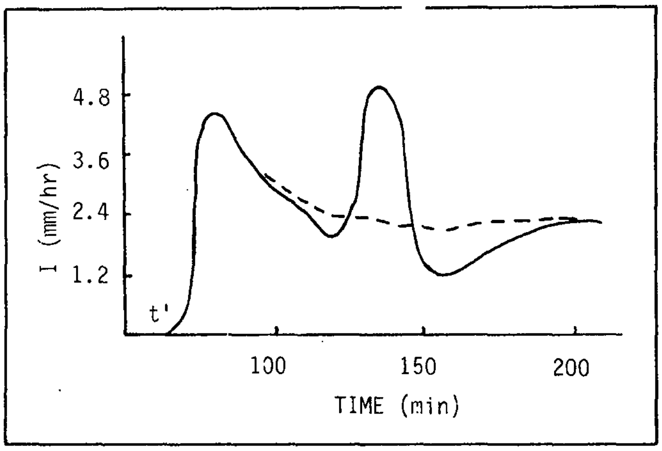

Figure 5. Evolution of Precipitation rate at Cloud Base in Salt Seeding Case

5.3 Seeding effects under different conditions

Calculations show that (1) the value and continuance of artificial rain peaks are larger in deep clouds, (2) the absolute value of artificial rain is larger but its relative value and continuance are less in clouds where the drafts are stronger, (3) the artificial rain is less in clouds where turbulence is stronger; (4) the seeding time (t') has little influence on the seeding effect, (5) the seeding effect is larger when the seeding height is relatively low (at 1.3 km in cloud with depth of 1.8 km), (6) the effect of seeding with a rate of 10^{-4} g/kg is better than that of 10^{-5} g/kg, and (7) the effect of seeding with R_{ho}= 6 μm is better than R_{ho}=12 μm, assuming the same seeding rate.

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