Study of Optimal Scheme in Cannon Precipitation Enhancement

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Abstract

One of the important problems in precipitation enhancement by the use of cannon is to figure out operating parameters and affected area. Diffusion of a catalyzer injected with multiple cannon-shots is studied in this paper. Effective seeding areas using different eddy diffusivity coefficients, azimuth, elevation and wind speeds are simulated. Based on these calculations an operation method is put forward, i.e. cannonballs are shot against the wind in a semicircle with multiple rounds. The method has been programmed in the Cannon Precipitation Enhancement Operation Command System which can automatically determine effective seeding areas to facilitate assessment of precipitation enhancement.

1. INTRODUCTION

Precipitation enhancement by the use of cannon plays an important role in China's weather modification. By the end of 2006, the number of cannon used in precipitation enhancement reached 7071 in China. Successful precipitation enhancement operations depend on the scientific operation scheme, which consists of selection of suitable weather conditions, determination of operation area and timing, and also important, the shooting method and the number of shots.

In previous studies, Abshaev *et al.* (2003) analyzed the diffusion of a catalyzer (ice nucleating material) in convective clouds. Shen *et al.* (1983) studied the diffusion of catalyzer regarding exploded cannon shots as point-sources. Diffusion in seeding was also discussed by Yu *et al.* (2002). However, much work still needs to be done for application.

In order to improve cannon precipitation enhancement operations, a cannon precipitation enhancement scheme of practical use is brought forward based on a great number of numerical simulations. The scheme takes into account not only diffusion and transportation from point-sources, but also maximum affected areas with multiple shots at different azimuth and elevation angles. Sensitivity tests are conducted for parameters of large variability, providing a reference value for practical use. The scheme has been coded in the Cannon Precipitation Enhancement Operation Command System, which can determine automatically the optimum azimuth and elevation angles, proper number of shots and other operation parameters. The method of effective seeding area determination can also be used in cannon precipitation enhancement assessment.

A large amount of cannon are in use in China's precipitation enhancement field projects. For example, in Weifang, Shandong Province (see Appendix), the average distance between distributed cannon sites is only 20 to 30km. In precipitation enhancement operations, rainfall weather systems are studied as they approach, and operation areas are determined based on radar echo intensity. In Weifang, only areas with radar echo intensity (PPI) greater than 20dBz are selected for operations, and the operation level is where air temperature lies between -5 and -10℃.

The explosion delay time of cannon shots used in Chinese precipitation enhancement is 12s. Different elevations, explosion heights, and corresponding horizontal explosion distances are listed in Table 1. For example, when the elevation is 70°, explosion height is 4451m, and the horizontal distance between cannon site and explosion site is 1813m.

Table 1 Comparison table of elevation, horizontal explosion distance and explosion height Unit: m

Elevation	85º	80º	75º	70º	65º	60º	55º	50º	45º
h/x	4778/464	4711/924	4602/1375	4451/1813	4259/2232	4030/2631	3765/3004	3468/3349	3142/3663

2. THE MODEL

In cold clouds, an exploded cannon-shot is regarded as a point-source of catalyzer, the atmosphere is assumed isotropic, and catalyzer particle combination or capture by cloud drops are not considered. Suppose wind direction is parallel to axis *x*, the diffusion equation is (Shen, 1994):

$$\frac{\partial q}{\partial t}+u\frac{\partial q}{\partial x}-w\frac{\partial q}{\partial z}=K\left(\frac{\partial^2 q}{\partial x^2}+\frac{\partial^2 q}{\partial y^2}+\frac{\partial^2 q}{\partial z^2}\right)$$

where *q* is concentration of catalyzer, *K* is eddy diffusivity coefficient, *u, w* are wind speeds in direction of *x* and *z* respectively, *t* stands for time length from explosion. Given initial and boundary conditions:

$$\begin{cases} t=0,\ \ q=Q\delta(x)\delta(y)\delta(z-h); \\ z=0,\ \ q=0; \\ \sqrt{x^2+y^2+z^2}\to\infty,\ \ q=0. \end{cases}$$

In the equation, Q stands for nucleus creating rate ($3.3*10^{11}g^{-1}$), $\delta(x)$, $\delta(y)\delta(z-h)$ are δ functions, h is height of explosion, the solution is,

$$q=\frac{Q}{8\sqrt{(\pi tK)^3}}e^{\left[-\frac{(x-ut)^2}{4Kt}-\frac{y^2}{4Kt}-\frac{w_m{}^2 t}{4K}+\frac{w_m(z-h)}{2K}\right]}\times\left[e^{-\frac{(z-h)^2}{4Kt}}-e^{-\frac{(z+h)^2}{4Kt}}\right] \quad (1)$$

where w_m is maximum ascending speed, which is neglected, and only horizontal diffusion is considered in this study. Given Q, K, u and w, the time evolution of diffusion area can be simulated. In case of multiple point-sources, for the i th point source, whose coordinate is (x_i, y_i, h), equation (1) can be rewritten as follows:

$$q_i=\frac{Q}{8\sqrt{(\pi tK)^3}}e^{\left[-\frac{(x-x_i-ut)^2}{4Kt}-\frac{(y-y_i)^2}{4Kt}\right]}\times\left[e^{-\frac{(z-h)^2}{4Kt}}-e^{-\frac{(z+h)^2}{4Kt}}\right]$$

At the elevation of point sources, the concentration at (x, y, h) is $q = \Sigma q_i$.

In recent years, cold cloud observation experiments using Particle Measuring System (PMS) probes has been carried out in northern China (including Hebei province, Henan province, Shandong province, Qinghai province) (Hu, 2001). Results show that the number of ice crystals in clouds is mostly at the rank of 10^0-10^1L^{-1}. Based on previous studies, for effective seeding, the number of artificial seeded ice crystals should be equal to that of natural ice crystals. Therefore, the area with AgI concentration exceeding $10L^{-1}$ after diffusion is determined as the effective seeding area.

3. DIFFUSION RADIUS AND TIME

Shen *et al.* (1996) calculated eddy diffusivity coefficients in different cloud systems in northern China, and found that eddy diffusivity coefficients in the winter are smaller than those in the summer. Eddy diffusivity coefficients in the summer lie between 10-40 m^2s^{-1}, and the maximum value of eddy diffusivity coefficient in cumuliform clouds is between 83-125 m^2s^{-1}. To demonstrate the effect of different eddy diffusivity coefficients, areas of concentration of catalyzer AgI q>=10 L^{-1} are simulated multiple times, assuming K=20, 40, 80, and 100 m^2s^{-1}. Different asymmetrical single apex curves of effective seeding radius are shown for each *K* value in Figure 1.

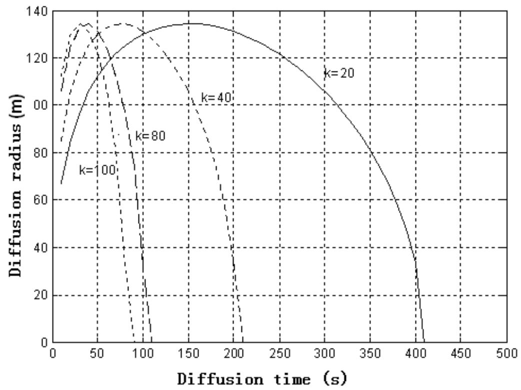

Figure 1. The changes of diffusion radius under different eddy diffusion coefficients.

The diffusion radius increases with time first, then decreases after reaching its maximum, and ultimately disappears. For different K values, the maximum value of diffusion radius is the same, which is 135m. For K equals 20, 40, 80 and 100m^2s^{-1}, diffusion radius reaches its maximum at 150.6s ,75.3s, 37.7s, and 30.1s respectively after explosion, and the time that the diffusion radius disappears is 411s, 206s, 103s, and 84s respectively.

4. EFFECTIVE SEEDING AREA

After explosion of a cannon shot, the diffusion of catalyzer AgI from the point-source is governed by two kinds of movements. The first is isotropic diffusion driven by turbulent eddies, and the second is advection driven by winds. Because maximum diffusion radius is the same under different eddy diffusivity coefficients, the diffusion area of each shot is only related to time, and different wind speed can only change the transportation distance. For example, when $k = 20m^2s^{-1}$, $v = 5m{\cdot}s^{-1}$, simulated areas of AgI consistency exceeding $10L^{-1}$ after explosion at different time of 10s, 75s, 150.6s, 320s, and 400s are shown in Figure 2. As the diffusion radius curve is a single apex, the effective seeding area expands first and then shrinks with time until it disappears. At 151s after explosion, the diffusion radius reaches its maxima as well as the effective seeding area. 411s after explosion, the area of AgI-generated crystals exceeding $10L^{-1}$ disappears.

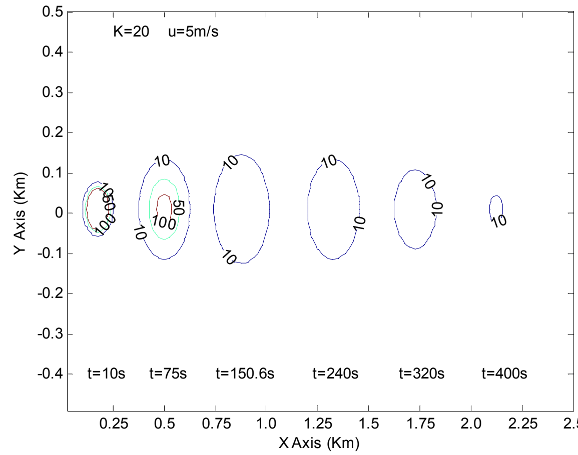

Figure 2. Horizontal distribution of AgI-generated crystals (L^{-1}) at different moments after explosion with $K = 20(m^2s^{-1})$, $\mu = 5(ms^{-1})$

The shape and location of the effective seeding area evolves with time. In order to improve and facilitate the determination of affected areas in operation assessment, the physical processes of particles in clouds are disregarded, and the effective area of shots is defined as the vertical ground projection of the accumulated area where AgI-generated crystals exceeds $10L^{-1}$ after explosion.

5. OPERATION SCHEME

5.1 Operation azimuth

In order to get the largest effective seeding area and save shots in cannon precipitation enhancement, a new operation method is put forward, i.e. repetitive multiple shooting upwind in a semicircle, as shown in Figure 3. As the catalyzer diffuses and moves leeward, gaps of effective seeding areas can be avoided by repetitive operations. The angle interval of shots is decided according to the principle that no gap is left between the effective seeding areas after diffusion. This operation method also facilitates assessment of operation results after operation.

5.2 Operation elevation and the number of shots

In precipitation enhancement operations, operation height can be chosen at the levels in clouds with temperatures between –5°C and –10°C. After operation height is determined, operation elevation is decided ac-

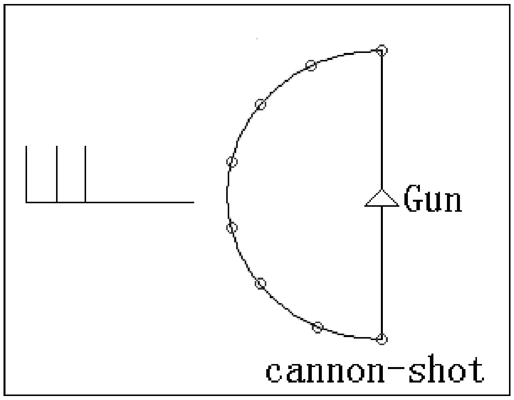

Figure 3. Sketch of operation azimuth. The triangle is the position of the gun; the circles show the positions of the exploded shots delivered at different azimuths.

cording to the parameters of cannon shots. Then the number of shots for maximum effective seeding area is calculated based on the principle of consistency of effective seeding areas.

According to the relationship between shot range and shot height, the horizontal shot range increases as elevation decreases. In order to get a larger effective seeding area, lower elevation should be used, and azimuth interval between shots should also be decreased while the number of shots increases. Based on the principle of consistency of effective seeding areas, simulations are carried out with different elevations, and the number of shots is given in Table 2. With an elevation of 80º, only eight shots at equal intervals in the semi-circle are needed to get maximum effective seeding area, while 21 shots are needed as the elevation decreases to 60º.

Table 2. Number of shots under different elevations

Elevation	Number of shots
85º	5
80º	8
75º	12
70º	15
65º	18
60º	21
55º	24
50º	27
45º	29

5.3 Time interval of operation

The effective seeding area only exists for a short time period after the explosion of each shot. Its lifetime changes with different eddy diffusion parameters. Therefore, the time intervals between rounds of shots should be determined based on different eddy diffusivity coefficients. According to Figure 1, with K equals 20, 40, 80, and 100m^{2}s^{-1}, time interval between rounds of shots in operation should be 411s, 206s, 103s, and 84s respectively.

6. AREA OF EFFECTIVE SEEDING

6.1 Effect of eddy diffusivity coefficients on effective seeding area

The diffusion equation shows that eddy diffusivity coefficient and effective seeding area are inversely proportional to wind speed when time is fixed. The larger the eddy diffusivity coefficient, the shorter the time it takes for the catalyzer to reach maxima diffusion radius, and the smaller the effective seeding area. Simulated effective seeding areas under different eddy diffusivity coefficients are shown in Figure 4. For the same wind speed (15m·s^{-1}) and elevation angle (65º), different eddy diffusivity coefficients (20 m^{2}s^{-1}, 40 m^{2}s^{-1}, 80 m^{2}s^{-1}, 100 m^{2}s^{-1}) result in different effective seeding areas of 26km^2, 13km^2, 6km^2, and 5km^2 respectively.

6.2 Effect of wind speed on effective seeding area

The surrounding wind field controls the advection of catalyzer. With fixed eddy diffusivity coefficient and operation elevation, the higher the wind speed is and the longer the distance the effective area covers, the larger effective seeding area is. Figure 5 shows the simulated effective seeding areas with the same eddy diffusivity coefficient (20 m^{2}s^{-1}) and elevation angle (80º), but different surrounding wind speed of 5m·s^{-1}, 10m·s^{-1},15m·s^{-1}, 20m·s^{-1} respectively.

Multiple simulations were conducted with a combination of different elevation angles, eddy diffusivity coefficients, and wind speeds. The areas of effective seeding are listed in Table 3. For example, with K = 20 m^{2}s^{-1}, u = 20 m·s^{-1} and the elevation of 60º, each shot gets an effective seeding area of 39km^2 .

Table 3. Comparison table of eddy diffusive coefficient, wind speed and effective seeding area (unit: km^2)

elevation		85°	80°	75°	70°	65°	60°	55°	50°	45°
K=20 (m^{2}s^{-1})	10 m/s	4.29	7.71	11.31	14.46	17.46	20.46	23.25	25.86	28.17
	15 m/s	6.35	11.37	16.70	21.50	25.64	30.08	34.71	38.36	41.60
	20 m/s	8.42	14.73	21.75	28.35	33.72	39.42	45.54	50.55	54.78
K=40 (m^{2}s^{-1})	10 m/s	2.21	3.84	5.82	7.38	8.88	10.26	11.88	13.05	14.19
	15 m/s	3.12	5.70	8.37	10.68	12.7 7	15.08	17.34	19.16	20.69
	20 m/s	4.13	7.41	10.89	14.12	16.82	19.83	22.67	25.25	27.35
K=80 (m^{2}s^{-1})	10 m/s	1.14	2.01	2.97	3.83	4.55	5.27	6.00	6.68	7.19
	15 m/s	1.55	2.90	4.26	5.39	6.41	7.53	8.78	9.54	10.35
	20 m/s	2.03	3.60	5.34	6.98	8.21	9.81	11.16	12.33	13.56
K=100 (m^{2}s^{-1})	10 m/s	0.93	1.58	2.51	3.09	3.71	4.26	4.76	5.46	6.03
	15 m/s	1.25	2.34	3.42	4.34	5.15	6.18	7.08	7.74	8.40
	20 m/s	1.70	2.93	4.22	5.52	6.75	7.76	9.02	9.86	10.73

7. ISSUES OF APPLICATION

In the cannon precipitation enhancement scheme discussed above, the eddy diffusivity coefficient and surrounding wind speed have great influence on effective seeding area. However, the real eddy diffusivity coefficient and surrounding wind field cannot be obtained directly before operations.

Shen *et al.* (1996) computed eddy diffusivity coefficient of cumulostratus in Hebei province in the summer half year, and revealed that the probability of eddy diffusivity coefficient less than 10m^{2}s^{-1} is 40%, and 30% for eddy diffusivity coefficient between 10-20 m^{2}s^{-1} . Therefore, when operating in cumulostratus, the eddy diffusivity coefficient is usually taken empirically as 20m^{2}s^{-1}, and in clouds of strong convections the value is set to 80 m^{2}s^{-1}. In Cannon Precipitation Enhancement Operation Command System, five ranks of eddy diffusivity coefficients ranging from 20 to 100 m^{2}s^{-1} are provided (Wang and Huang, 2007).

There are always no wind observations at the position of the exploding shells at the time of operation. It is practical to substitute for it with data of neighboring levels or from a numerical weather prediction model forecast. An input window for value of surrounding wind is provided in Cannon Precipitation Enhancement Operation Command System.

After eddy diffusivity coefficient, wind direction, wind speed, and operation height are determined and input, based on the scheme above, Cannon Precipitation Enhancement Operation Command System will automatically calculate and display the azimuth, elevation, and number of shots on different operation spots.

8. CONCLUSIONS

(1) Based on the principle that the number of artificial ice crystals should be equal to that of natural ice crystals, the vertical ground projection of the accumulated area where AgI-generated crystals exceeds 10L^{-1} after diffusion is calculated and can be defined as the effective area.

(2) Operation azimuth is decided based on the operation method, in the case considered here it is shooting upwind in a semicircle with equally spaced intervals. Operation elevation angle is decided based on operation height. The proper number of shots is calculated based on the principle that no gap is left between the effective seeding areas. Precipitation enhancement should be operated with multiple rounds at time intervals determined based on lifetime of effective areas, in order to get maximum effective seeding area.

(3) The operation scheme and Cannon Precipitation Enhancement Operation Command System provide an automated and scientific way of cannon precipitation enhancement.

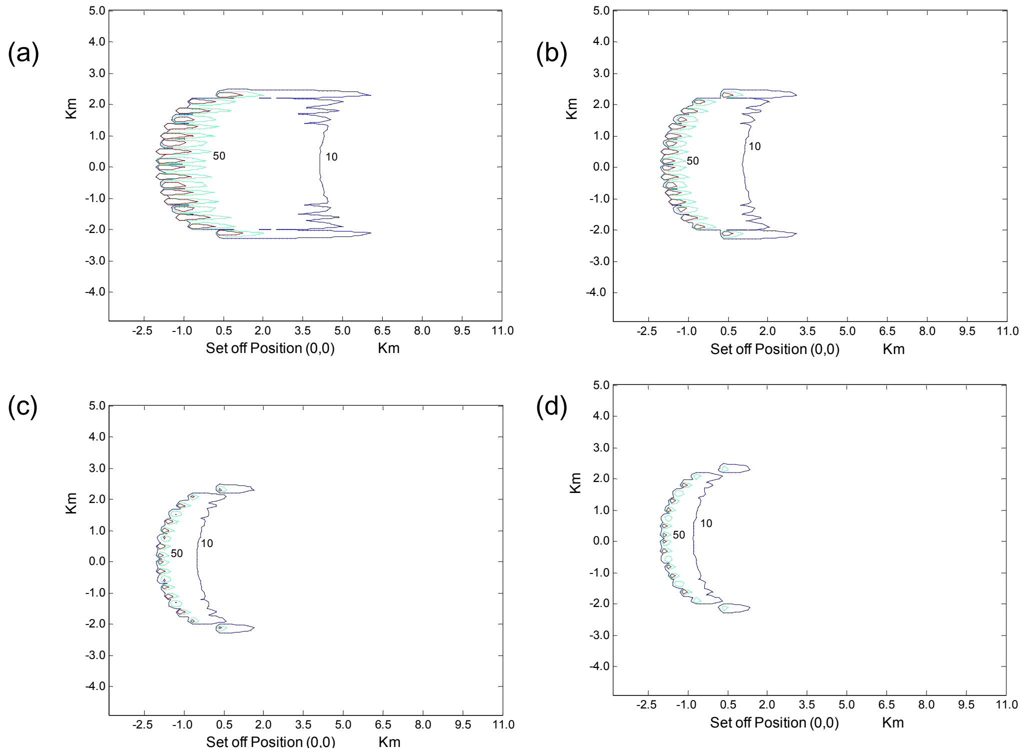

Figure 4. Simulated effective seeding areas enclosed by contours of 10 L^{-1} (dark blue) and 50 L^{-1} (light blue) under different eddy diffusivity coefficients (wind speed is 15$m \cdot s^{-1}$, and elevation is 65º) (a) K=20 m^2s^{-1}, (b) K=40 m^2s^{-1}, (c) K=80 m^2s^{-1}, (d) K=100 m^2s^{-1}.

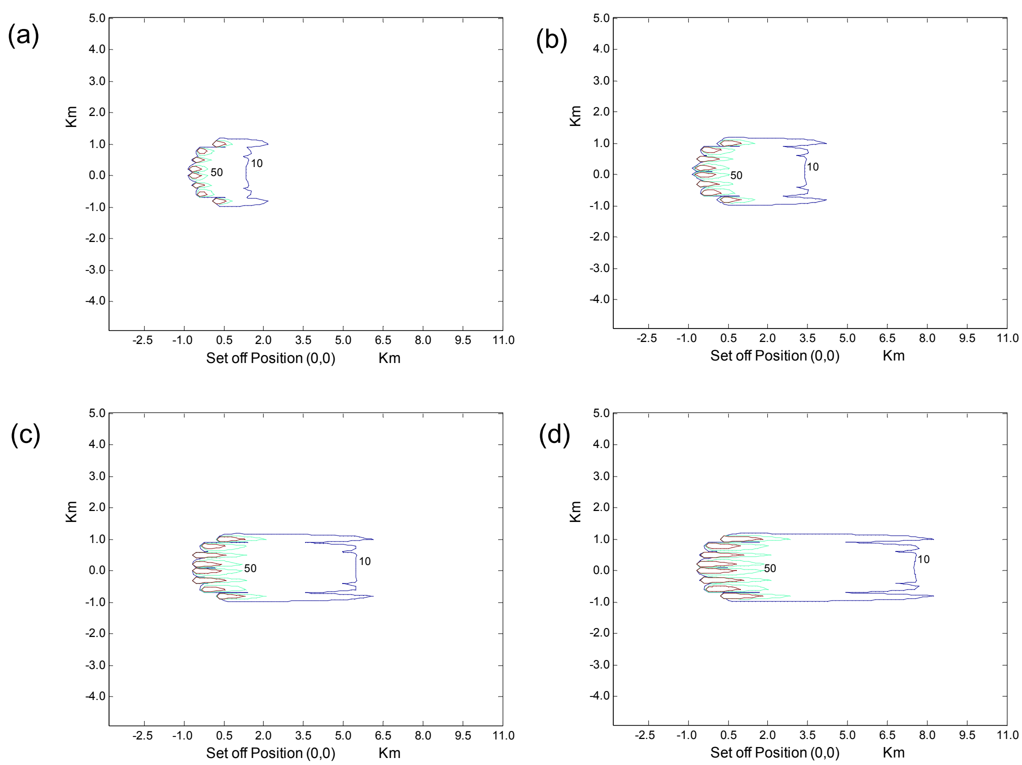

Figure 5. Simulated effective seeding areas (as in Figure 4) under different wind speeds (K=20 m^2s^{-1}, elevation 80º) (a) u = 5$m \cdot s^{-1}$, (b) u = 10$m \cdot s^{-1}$, (c) u = 15$m \cdot s^{-1}$, (d) u = 20$m \cdot s^{-1}$.

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Appendix Map of China and Shandong province