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A Numerical Model To Investigate Optimum Liquid Carbon Dioxide Seeding Rate In Weather Modification Projects

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Atmosphere is a dynamic fluid in which natural processes such as movement of air mass, formation of natural cloud and precipitation occur , and where weather modification is focused on possibility of control on natural processes of atmosphere. Cloud models have different types of application in operational weather modification programs such as; hypothesis development, assessment of seedability, experimental design, operational decisions, project evaluation, as well as understanding of seeding effects. Therefore, in this research, numerical modeling for optimal utilization of phase change energy in ice thermal induced by Liquid Carbon Dioxide (LCD) in supercooled cloud seeding as suggested in Javanmard et al. (1998a) has been applied. In this article, after a short review on application of numerical modeling in weather modification activities, numerical modeling of the Roll-up Expansion of Twin Horizontal Ice crystal Thermal (RETHIT) process which forms in LCD seeding has been presented. It includes the dynamics, microphysics, and procedure of calculation of the model. Then in order to assess optimal seeding rate in supercooled cloud seeding using LCD, the above mentioned RETHIT numerical model which is written in Fortran language has been applied. The model has been run for the three seeding rates of (PL) 40 g/s, 100 g/s, and 260 g/s. Finally, the output results of the microphysic and dynamic parameters of the formed ice thermal has been discussed.

The above mentioned results of the numerical model has shown that the arriving time of ice thermal at the cloud top is about 16 min in PL=40, 15.4 min in PL=100, and 17.2 min in PL=260, which is very close to the LCD seeding experiment results which have been obtained by Tomine et al. (1998); they are also in accordance with the metaldehyde seeding experiment results obtained by Fukuta (1972). As a result, the calculated optimum seeding rate by LCD seeding model is 40 g/s, which could help in determining the threshold value of seeding rate, and which avoids overseeding effects as well as economic benefits.

INTRODUCTION

Atmosphere is a dynamic fluid in which natural processes such as movement of air mass, formation of natural cloud and precipitation occur and where weather modification is focused on possibility of control on natural processes of atmosphere. Weather modification activities conducted in a number of countries were aimed at improving economy (for example, to increase water supply for agriculture) or reducing the risks associated with high impact weather (frost, fog, hail, etc.). In the 15th World Meteorological Organization (WMO) Congress in 2007, it was strongly recommended that such activities should be supported by research that

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provides: (a) a deeper understanding of the effects of cloud modification on cloud/precipitation development; and (b) a scientifically accepted evaluation of weather modification activities (WMO, 2007). In order to achieve the most effective and successful results from weather modification projects, cloud behavior and its reaction to various types of seeding could be determined using numerical modeling. In this paper, our previously developed numerical model of supercooled cloud seeding using liquid carbon dioxide (LCD) (Javanmard et al.; 1998a, 1998b, 1999) has been applied to compare the impact of LCD seeding rate on the dynamical and microphysical factors of the ice thermal induced due to the seeding.

Optimization of microphysics-dynamics interactions in induced artificial processes is necessary for precipitation development and associated effects in ice phase weather modification, (Fukuta, 1998). In this regard, the LCD seeding method of effectively and continuously supplying the necessary energy in the form of the latent heat of phase change during the seeding reaction has been formulated in view of optimal use and combination of the reactions and conditions involved in horizontal penetration seeding of liquid homogeneous ice nucleate at a low level of the supercooled zone (Fukuta, 1997). The seeding leads to the RETHIT process followed by falling-growth induced lateral air spreading (FILAS) at the cloud top (Fukuta, 1998), which was tested in supercooled stratus clouds and fogs with marked results (Fukuta, 1996).

The physical basis for fundamental processes involved in the formulation of the phase change energy utilization mechanism to optimize seeding effect applicable for supercooled cloud has been introduced by Javanmard et al. (2003). The developed method satisfies the feedback conditions, and causes roll-up expansion of twin horizontal ice crystal thermals (RETHIT), with a horizontal penetration seeding of homogeneous ice nucleants LCD which has already been tested with marked results. In this regard, we can refer to such experiments as seeding of the superecooled convective clouds with LCD under outbreak of cold air mass from Siberia in Northern Kyushu, Japan, on February 1999. Under the above mentioned condition, tracing of radar images has confirmed the formation of two artificial radar echoes. (Nagata and et al., 2004). Moreover, according to the Western Kansas Weather Modification Program (WKWMP), testing of the experimental LCD method began on August 20^{th} , 2003. Therefore, as it has lower operation costs, LCD seeding technique was then supposed to be implemented in an operation in near future in Western Kansas (Water District Newsletter, 2003).

In this respect, numerical modeling for optimal utilization of phase change energy in ice thermal induced by LCD in supercooled cloud seeding on the basis of Javanmard et al. (1998a) has been applied. After a short review on application of numerical modeling in weather modification activities, numerical modeling of the Roll-up Expansion of Twin Horizontal Ice crystal Thermal (RETHIT) process which forms in LCD seeding will be presented. It includes the dynamics, microphysics, and procedure of calculation of the model. Then for the purpose of assessment of optimal seeding rate in supercooled cloud seeding using LCD, RETHIT numerical model which was, as mentioned earlier, encoded in Fortran language would be applied. The model will be run for the following three seeding rates (PL) of 40 g/s, 100 g/s, and 260 g/s. Finally, the output results of the microphysical and dynamical parameters of the formed ice thermal would be discussed.

APPLICATION OF NUMERICAL MODELING IN WEATHER MODIFICATION ACTIVITES

Recent advances in computer hardware, software, and physical understanding have allowed improvements in two- and three- dimensional numerical models which simulate cloud processes. These models continue to provide an ever-improving understanding of the complicated interactions within both natural and seeded clouds. Numerical simulations are now able to replicate many of the details observed in actual clouds. The impacts on cloud and precipitation development resulting from slight variations in cloud microphysical or dynamic characteristics can be produced for the same cloud, for both natural and seeded circumstances. This is the only method in which identical clouds can be studied in both treated and untreated versions, which may lead to more confident prediction of seeding effects and thus, improved selection criteria for candidate clouds (AMS, 1996).

The numerical modeling of clouds has a history almost as long as the modern-day concepts of the seeding of clouds. Orville (1996) discussed that the models could be classified as Zero-, one-, two-, and Three-dimensional (0D, 1D, 2D, 3D), and time-dependent or steady –state (TD or SS). They can be either coupled or uncoupled with respect to the microphysics and dynamics. The cloud models have six types of application in weather modification: hypothesis development, assessment of seedability, experimental design, operational decisions, project evaluation, and understanding of seeding effects. As an example, the reader is referred to application of a one-dimensional cloud and hail model to forecast maximum hailstone diameter for Mendoza, Argentina. A one-dimensional, steady-state cloud model was combined with a time-dependent hail growth model to predict maximum hailstone diameter at the ground. The forecast hailstone diameters have been compared with daily observations of maximum hail size for the Mendoza Hail Suppression Program in Argentina during the 1999-2000 hail season (Brimelow and Krauss, 2001).

Modern direct and remote sensing techniques could give detailed information on cloud structure and physical quantities such as phase (water-vapour-ice), wind speed and its direction. Doppler and polarisation radar could be used to study non-precipitating clouds and evolving cloud cells, microwave radiometer profilers measure liquid water content, and satellite data could be used to intervene detailed measurement points. These data can be fed into detailed cloud models for prediction and verification of seeding impacts (Department of Environment and Conservation (DEC), Sydney, 2007).

NUMERICAL MODELING OF RETHIT PROCESS

Dynamical Process

Figure 1 shows the RETHIT effect of the seeded ice thermal during the ascent. The ice thermal motion is essentially the same as cumulus convection, except that the thermal is in the form of a horizontal line at the beginning of seeding. As the thermal rises, it becomes twin cylinders due to the buoyant force acting at the center instead of toroidal shape of the cumulus convection (Fukuta, 1998b). The twin cylinders of ice thermal roll up and expand while entraining the surrounding supercooled cloud with the help of generated eddy field and sustaining ice crystal growth for generation of latent heat which in feedback powers the roll-up expansion. If the cumulus is applied, the semi-vertical angle of the expansion should be about 15^o (Emanuel, 1994). In cylindrical case, the angle is derived about 17.65^o. The updraft velocity of the ice thermal would be determined based on the bubble theory as:

$$W = c(gBR)^{\frac{1}{2}} \ , \tag{1}$$

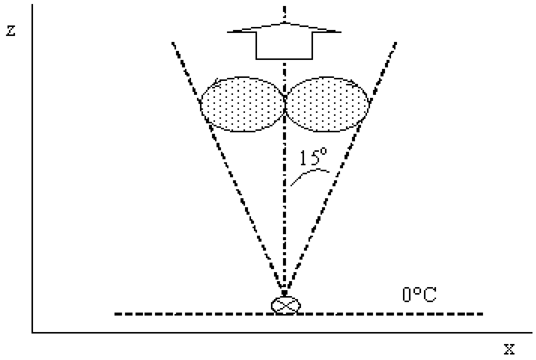

Figure 1. The process of Roll-up Expansion of Twin Horizontal Ice-crystal Thermal (RETHIT) in the optimized seeding (Fukuta, 1999)

where $B = \frac{(T_p - T_c)}{T_c}$ is the buoyancy factor, T_p the ice thermal temperature, T_c the ambient cloud temperature, and R the diameter of the cylinder, c is assumed to be 1.2, but there are some uncertainties associated with it; the value was independent of the Reynolds number and approximately constant according to water tank experiments (Scorer, 1957). As the radius of ice crystals is less than $30\mu m$ and spherical, the ice crystals fall velocity has been determined according to Stokes' Law as follows;

$$V_T = k_1 r^2 \tag{2}$$

where $k_1 \cong 1.19 \times 10^6 cm^{-1}s^{-1}$.

Microphysical process

When ice crystals co-exist with supercooled water droplets, the system undergoes a change. Since the equilibrium vapor pressure over ice is less than that over water at the same temperature, the drops evaporate into vapor and consequently the ice crystal grows by diffusion process of the vapor according to Bergeron (1949). The process stops when a thermodynamic equilibrium is achieved after exhausting the droplets and generating heat of the phase change. Therefore, the total amount of ice crystal growth, as shown below, does not exceed the amount the thermodynamic limitation:

$$\Delta W_s \geq \Delta W_{DF} \ , \tag{3}$$

where ΔW_s is the ice water content of the thermodynamic limitation and ΔW_{DF} is the total ice water content by ice crystal growth. Ice water content of the thermodynamic limitation should be determined by the following equation which is based on the theory of Fukuta (1949).

$$\Delta W_S = W_L + \frac{\rho_a C_{pd}}{L_d} \Delta T_d \ , \tag{4}$$

where W_L is liquid water content (per unit volume) in ice thermal, ρ_a the air density, C_{pd} the specific heat at constant pressure, L_d the specific latent heat of deposition, and ΔT_d given as:

$$\Delta T_d = \frac{\left[\frac{(S_i - 1) R_d T}{\epsilon L_d} - \frac{L_f W_L}{\rho a C_{pd}}\right]}{\left[1 + \frac{C_{pd} R_d T^2}{\epsilon \, qis(T) L_d^2}\right]} \ , \tag{5}$$

where S_i is ice saturation ratio, R_d the specific gas constant of dry air, ϵ the ratio of specific gas constant of dry air to specific gas constant of vapor, L_f the specific latent heat of fusion, and q_{is} the ice saturation mixing ratio.

$$S_i = \frac{e}{e_{is}} \tag{6}$$

$$q_{is} = \epsilon \frac{e_{is}}{p} \tag{7}$$

Procedure of Calculation

The model is time–dependent, two dimensional, covering a region of 10 square km. We assume that a supercooled cumulus cloud has been already formed and liquid water content as constant with height. The ice crystals are assumed in spherical shape. The initial radius of ice crystal after ice nucleation is assumed 1μm with the density $\rho_i = 0.917$g/cm^3. In the model, four process are considered in a time interval of 5 s as follows (Javanmard et al., 1998a)

- *First Process*

Ice thermal moves upward by the buoyancy calculated in the previous time step, and its volume expands. Temperature and vapor pressure in ice thermal would be determined according to the dry adiabatic process.

- *Second Process*

By isobaric mixing of ice thermal of the previous time step and entrained supercooled cloud, the variables of temperature (T) and water vapor density (ρ_v) and liquid water content (W_L) after mixing are calculated in the following manner:

$$T^{(t)} = \frac{V^{(t-\Delta t)}T^{(t-\Delta t)} + \Delta V^{(t)}T_e^{(t)}}{V^{(t)}} \tag{8}$$

$$\rho_v^{(t)} = \frac{V^{(t-\Delta t)}\rho_v^{(t-\Delta t)} + \Delta V^{(t)}\rho_{ve}^{(t)}}{V^{(t)}} \tag{9}$$

$$W_L^{(t)} = \frac{V^{(t-\Delta t)}W_L^{(t-\Delta t)} + \Delta V^{(t)}W_{Le}^{(t)}}{V^{(t)}} \tag{10}$$

where, t is time, Δt is the time step of the computer program. The subscript e denotes the entrained cloud into the ice thermal.

- *Third Process*

Supercooled water droplets entrained in the ice thermal evaporate according to the Diffusion-Kinetic theory. Fukuta and Walter (1970) developed a method that is now widely used to allow for kinetic effects in droplet growth calculations. Their approach requires two new parameters that characterize the molecular transfer of heat and vapor: the accommodation coefficient α and the condensation coefficient β. The growth rate of cloud droplet including Kinetic theory correction has been defined as :

$$r\frac{dr}{dt} = \frac{S-1}{\left[\left(\frac{L}{R_vT}-1\right)\frac{L\rho_L}{KTf(\alpha)} + \frac{\rho_L R_v T}{De_s(T)g(\beta)}\right]} \tag{11}$$

Where S is the ambient saturation ratio as follows:

$$S = \frac{e}{e_s(T)} \tag{12}$$

Where e is vapor pressure and e_s is saturation vapor pressure over cloud droplet. L is latent heat of vaporization, T, temperature, R_v is individual gas constant for water vapor, ρ_L is liquid water density, D is molecular diffusion coefficient, K is coefficient of thermal conductivity of air. $f(\alpha)$ and $g(\beta)$ are normalized factor of kinetic-diffusion correction. For small drops $f(\alpha)$ and $g(\beta)$ are less than unity and the kinetic effects are a barrier to growth. As r increases, these factors approach unity and the above equation reduces to the continuum solution.

The evaporated amount per volume must not exceed the thermodynamic limitation and the liquid water content in the ice thermal.

- *Fourth Process*

The ice crystals grow according to the theory of the steady –state growth of a spherical drop at rest in a vapor field regarded as a continuum which is often called the Maxwell theory assuming the shape of ice crystal is spherical. The growth rate is as follows:

$$\frac{dM}{dt} = \frac{4\pi C(S_i-1)}{\left[\left(\frac{L_s}{R_vT}-1\right)\frac{L_s\rho_L}{KT} + \frac{\rho_L R_v T}{De_i(T)}\right]} \tag{13}$$

This formula is precisely the same as was obtained for water droplets, if we replace r with C, $e_s(T)$ by $e_i(T)$ and L by L_s the latent heat of sublimation and the kinetic effect and ventilation are neglected.

We have also assumed that the grown amount per unit volume must not exceed the thermodynamic limitation.

Results

Initial Condition

The numerical model has been run for three LCD seeding rates (PL) 40 g/s, 100 g/s, and 260 g/s. Cloud condition is assumed as follows: the embedded cumulus cloud has a 3 km thickness with the height of the cloud base 2 km and its temperature is 0°C. Temperature in the cloud decreases with height along the moist adiabatic. The liquid water content is set to 0.5 g/m^3 and all supercooled droplets have the radius of 6 μm. Droplets entrained in the ice thermal decrease in radius and finally disappear due to evaporation. It is assumed that the number of ice crystals generated by LCD is $n = 10^{13}$g^{-1}, and the speed of aircraft is $U = 100$m/s. Horizontal penetration seeding using LCD is carried out at -1°C isotherm in the model, and the program has been run for three following seeding rate (PL) 40 g/s, 100 g/s, and 260 g/s. The initial cloud and LCD seeding condition are shown in Table 1.

Output model run for following the cases, case 1: 40 g/s, case 2: 100 g/s, and case 3: 260 g/s

After LCD seeding, the ice thermal formed expands its volume entraining and consuming the ambient supercooled cloud, and reaching the cloud top in 16

Table 1. Initial condition of cloud and LCD seeding in the model

No.	Parameter	Value	
1	Cloud Base Height	2 km	
2	Cloud Base Temperature	0° C	
3	Initial Supercooled Droplets Radius	6 μm	
4	Cloud Thickness	3 km	
5	Liquid Water Content	0.5 g/m^3	
6	Horizontal Penetration LCD Seeding Level	-1°C Isotherm	
7	Speed of Air Craft (U)	100 m/s	
88	Number of Ice Crystals generated by LCD (n)	10^{13} g^{-1}	
9	LC seeding rate (PL)	**No. of Cases**	**PL (g/s)**
		1	40
		2	100
		3	260
10	Intensity of the Ice Crystals Line Source (S=nP/U)	**No. of Cases**	**S(m^{-1})**
		1	4*10^{13}
		2	1*10^{13}
		3	26*10^{12}

min., 15.42 min., and 17.75 min. for LCD seeding rates (PL) 40 g/s, 100 g/s, and 260 g/s , respectively, as shown in Figure 2.

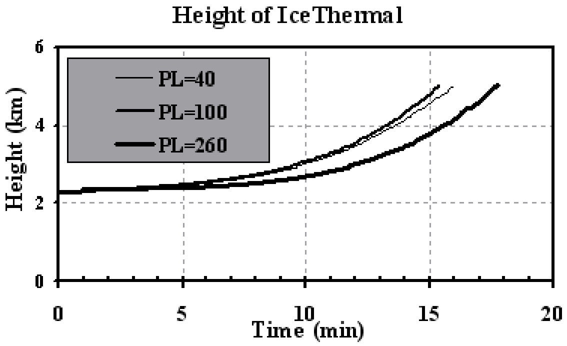

Figure 2. Height of the formed ice thermal for three run cases as follows: case 1: PL=40 g/s, case 2: PL=100 g/s, case 3: PL=260 g/s.

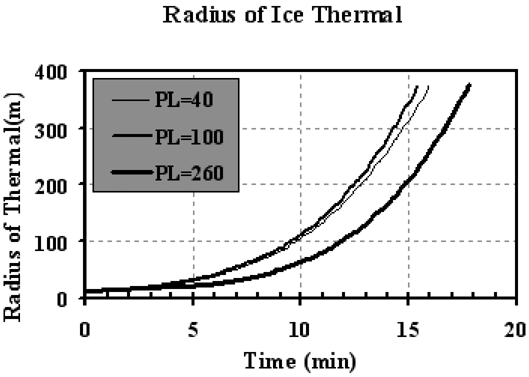

Figure 3. Figure 3. Radius of the formed ice thermal for three run cases as follows: case 1: PL=40 g/s, case 2: PL=100 g/s, case 3: PL=260 g/s.

The radius of the ice thermal increases by time, and becomes about 374 m, 372 m, and 373 m (The diameter of cylinder becomes 748 m, 744 m, 746 m) for case 1, case 2, and case 3, respectively, as shown in Figure 3, where the temperature of cloud top is approximately -20°C in three cases as shown in Figure 4. The vertical velocity of the ice thermal increases linearly with time as the buoyant force becomes stronger (Figure 5). Near the cloud top, the vertical velocity attains a maximum of approximately 7.94, 8.71, 9.14 m/s in case 1, case 2, and case 3 respectively, as shown in Figure 5, where the temperature difference between the ice thermal and the supercooled,cloud reaches a maximum value of approximately 0.610 °C, 0.740 °C, 0.790 °C in case 1, case 2, and case 3 respectively (Figure 6). This shows that less PL leads to less maximum latent heat, which in turn generates less maximum ice thermal updraft velocity. There is a direct relationship between maximum ice thermal updraft velocity and amount of PL. The mass of ice crystal in the three seeding rates of (PL) 40 g/s, 100 g/s, and 260 g/s reach a maximum amount of 0.18 μg, 0.07 μg, and 0.03 μg respectively (Figure 7). It shows that increasing the amount of LCD seeding rate is associated with increasing density number of ice crystal (No. of ice crystals per unit volume), and low

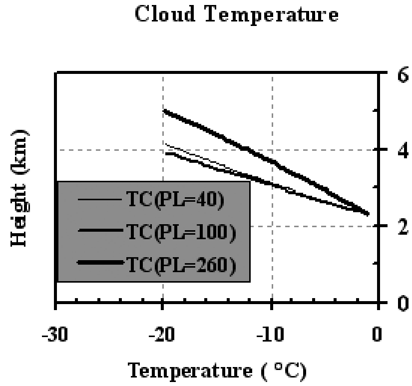

Figure 4. Vertical profile of cloud temperature in in three run cases as following; case 1: PL=40 g/s, case 2: PL=100 g/s, and Case 3: PL=260 g/s.

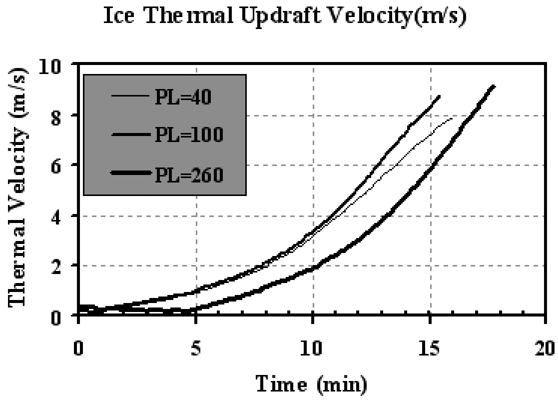

Figure 5. Figure 5. Ice thermal updraft velocity (m/s) in three run cases as following; case 1 : PL=40 g/s, case 2: PL=100 g/s, and case 3 : PL=260 g/s.

mass of ice crystal, whereas decreasing the amount of LCD seeding r ate is associated with decreasing density number of ice crystal and higher mass of ice crystal.

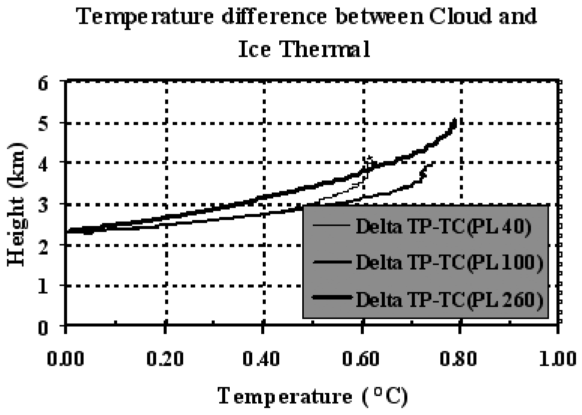

Figure 6. Temperature difference between cloud and ice thermal in three run cases as following; case 1: PL=40 g/s, case 2: PL=100 g/s, case 3: PL=260 g/s.

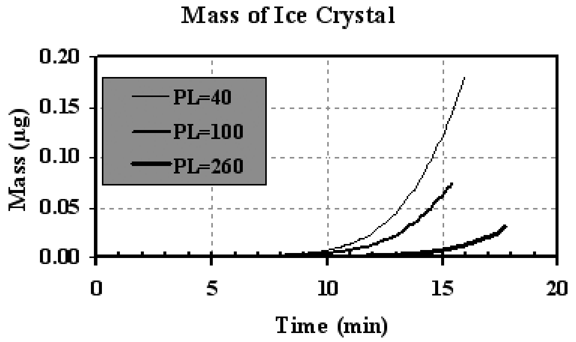

Figure 7. Mass of ice crystal in the formed ice thermal in three run cases as following; case 1: PL=40 g/s, case 2: PL=100 g/s, and case 3 PL=260 g/s.

Liquid water content in the ice thermal decreases rapidly for 5 minutes, and then drops to less than 0.50 g/m^3 (Figure 8). This shows that supercooled droplets entrained in the ice thermal are consumed effectively by the phase change process. In the above mentioned ice thermal, the ice crystals grow by the following two processes as shown in Figure 7.

During the early process, ice crystals compete with each other for the available vapor under the thermodynamic limitation; consequently, growth of each crystal is slow. In the later stage, ice crystals grow freely according to the Maxwellian theory, being independent of thermodynamic limitation. The competitive process continues for 12 min. for PL=40, and 14 min. for PL=100 because the final thermodynamic state keeps ice saturation at each time step and, on the other hand, the process of free growth becomes faster as ice saturation ratio increases rapidly after 5 min (Figure 9). The amount of physical parameters of ice thermal at the cloud top is shown in Table 2.

In regard of comparison of the numerical modeling results with the experiments, it should be noted that the objective of developing the above mentioned numerical modeling, which is unique and is carried out for the first time, is achievement of the necessary knowledge for numerical modeling of ph

Table 2. The amount of physical parameters of ice thermal at the cloud top in three run cases

Physical Parameters	**Case 1: PL=40 g/s**	**Case 2: PL=100g/s**	**Case 3: PL=260 g/s**
Time (min.)	16	15.4	17.8
Mass of Ice Crystal(μg)	0.18	0.07	0.03
Radius of Ice Crystal(μm)	36	26	19
Height of Ice Thermal(km)	5	5	5
Radius of ice Thermal(m)	374	372	373
Ice Thermal Updraft Velocity(m/s)	7.94	8.71	9.14
Cloud Temperature	-19.9	-19.8	-19.9
Ice Thermal Temperature	-19.3	-19.1	-19.1
Ice Saturation Mixing Ratio	1.07	1.03	1.00
Ice Crystal Fall Velocity(m/s)	0.14	0.08	0.04

Liquid