J. Basic. Appl. Sci. Res., 2(7)7328-7342, 2012
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ISSN 2090-4304
Journal of Basic and Applied Scientific Research
www.textroad.com

A Numerical Analysis of Homogeneous Cloud Seeding Agent Based on Sensitivity Tests in Different Conditions

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ABSTRACT

In this study, a numerical analysis of homogeneous cloud seeding agent on the one-dimensional, time-dependent cloud model is carried out. Sensitivity tests are done for different seeding methods, cloud life stages, seeding positions, and in the two kinds of cumulus clouds in which one of them is a mixed cloud. In this study, feasibility of rainfall enhancement and hail/graupel suppression due to glaciogenic seeding with homogenous agent is analyzed. Moreover, changes of hydrometeors mixing ratios with respect to the seeding methods for different clouds are studied. In addition, the effects of different seeding positions, including seeding at the base, middle and top of the clouds on microphysical and dynamical processes are analyzed. The results of analyses with respect to seeding time show that cloud seeding in the early mature stage of the cloud life cycle is sensitive to the seeding position. Numerical analyses also, indicate, depending on the cloud top level and seeding method, rainfall enhancement amount can vary from 1% to 52%. In the present work, more effective seeding method and seeding position for different conditions are obtained in this work .The results also show, sensitivity of rainfall intensity to different seeding positions and different kinds of clouds. The results of this study are verified by other studies wherever possible.

KEY WORDS: Homogenous ice nucleation; Glaciogenic Seeding; rainfall enhancement; rainfall intensity; microphysical and dynamical processes

INTRODUCTION

Clouds play a crucial role in the dynamic and thermodynamics of the atmosphere. Precipitation from clouds is of vital importance for human life and activity. Latent heat release is one of the main energy sources for atmospheric phenomena of different spatial scales ranging from individual clouds, to mesoscale systems. The rate of latent heat release and processes of precipitation formation are affected by microphysical processes of formation, growth and interaction of drops and ice particles [1]. Nowadays, in many countries around the world, cloud seeding operations have been widely used to modify cloud's processes with the aim of rainfall enhancement and hail/graupel suppression. In a study carried out by Gharaylou . (2010) , it was found that rainfall modeling and microphysical and dynamical processes, especially cumulonimbus clouds seeding are very important in small scale modeling because of the great amount of precipitations in short periods and smaller size of this kind of cloud compared to the grid's dimensions in mesoscale models [2]. In another study, stated that precipitation of convective clouds in tropical countries due to maximum rainfall production during the year and the release of the maximum latent heat is of great importance[3]. Aforementioned studies, highlight the importance of convective clouds in the cloud seeding operations in tropical countries.

Convective clouds seeding can be done in two methods: static and dynamic seeding [4]. Although the rainfall enhancement has been confirmed by glaciogenic seeding method in many cloud seeding field operations e.g. English and Marwitz [5]. There are still many unknowns in this field [6,7]. Numerical cloud models are important tools for weather modification research [8,9]. which can be used for cloud seeding concepts development, operational decisions, project evaluation, understanding of seeding effects, seedability tests of clouds on something e.g. type of clouds, seeding types, seeding materials, seeding levels, seeding positions, duration of seeding and potential of cloud to produce precipitation. Seeding by dry ice reduces the growth time of ice crystals, because of the rapid fast updraft development within the vertically oriented thermals that are formed due to the vertical accumulation of buoyant force. Therefore, ice particles remain too small in the cloud top. In order to solve these problems, Fukuta (1996) suggested a method to seed the liquid carbon dioxide (hereafter , LCO_2) horizontally at

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the lower level of the super cooled portion of clouds to increase dynamic effects of seeding. Fukuta (1996) have examined this method on the fogs and shallow stratus clouds in Project Mountain Valley Sunshine in Japan[10]. Javanmard (1999) has simulated this theory by using two dimensional model with the aim of cloud seeding in low levels [11]. Wakimizu *et al.*(2002) have investigated the LCO_2 seeding effects on the supercooled convective cloud in northern Kyushu, Japan, 1999 , using the recorded radar data, artificial radar and thermodynamic diagrams in the operation [12]. Guo *et al.* **(**2006**)** tried to compare the effects of seeding by AgI and LCO_2 [13]. Seto *et al*., (2011) used WRF model, radar and satellite data and studied the seeding effects on one stratus cloud experimentally and numerically [14].

Although, there are great amount of developments in the clouds and thunderstorms modeling , there are many unknowns about glaciogenic seeding conditions and seeding effects on the clouds, specially by means of homogenous seeding agent. Since, precipitating cumuli can be as little as 1.5 km and as much as 19 km deep, different cumulus clouds have special features which highlights the importance and necessity of various seeding research on different kind of clouds with different thickness. It should be noticed that, previous studies were carried out for particular type of climate; region and more often on one special kind of cloud .This kind of research, are often useable, just for that special region or kind of climate. For instance, in cumulonimbus clouds, the thickness and position of cloud toward freezing level, provide different amount of initial ice concentration which can make mixed cloud. How much this difference in initial ice concentration is affective on the rainfall enhancement and hail suppression due to homogenous seeding, has not been studied yet. Moreover, dynamic effects of homogenous seeding agents and details of microphysical and dynamical processes have not been investigated for different seeding methods(modes of releasing seeding agent), time , and positions (top, middle, base of the clouds) in the clouds with different thickness numerically.

In this study, upper air data are adjusted as if different clouds with different thickness can be formed. Therefore, since seeding effects are dependent on conditions, various sensitivity tests are carried out in the present work, for achieving more details on the glaciogenic seeding by homogenous agent. This numerical analyses included, the no-seeding, point seeding (seeding the cloud at one point at an instant of time), and horizontal seeding (continuously seeding the cloud at several points) cases. The effects of seeding in different stages of cloud life cycle and different seeding positions (at the top, middle and base of clouds) are studied. Most of the results are demonstrated for two clouds including one mixed cloud and one deep convective cloud with cloud top level (hereafter, CTL) equal to 10.5 and 7km, respectively. Total amount of microphysical processes in different seeding conditions (seeding stages, seeding methods, seeding positions) are analyzed numerically. Meanwhile suitable seeding method regards to aim of seeding (rainfall enhancement or hail/graupel suppression) is obtained for different clouds.

MATERIALS AND METHODS

Model descriptions

The present model in this study is an extension of Pirhayati's model [15], which, in turn, is based on other investigators' model [Lin et al [16]; Hise [17]; Jamali and Javanmard [18]] , respectively. In the Pirhayati's model, the cloud is a rotating air column with 3km radius. In this model, the initial concentration of the cloud ice has been initialized based on the Cotton equation (1986) in terms of temperature and super-saturation ratios [19]. In the present study, microphysical and dynamical processes of the glaciogenic seeding by homogenous ice nucleation have been added to the model using the Gue *et al*. (2006), Cotton *et al*. (1986), and Hise *et al*. (1980) equations. The resulting model contains entrainment and detrainment effects, lateral and vertical eddy perturbation, auto conversion processes, melting, freezing, sublimation, evaporation, collision and coalescence, collision and aggregation, probabilistic freezing, Bergeron Findisen process, and natural and artificial accretion and deposition of particles. In this work due to the glaciogenic homogenous seeding, three microphysical processes are considered including, are the conversion of rain water into snow, conversion of cloud droplet into cloud ice, ad conversion of cloud droplet into ice precipitation. In addition to the thermal processes which are produced by interaction of the seeding agents with the cloud microstructure, two other cooling terms are also added to the energy equation. These two terms are due to the seeding of the liquid CO_2 at -90C° temperature. In this research, cloud seeding is simulated at *-1*C°, by the point and horizontal seeding methods. For the present model, vertical spatial step is considered to be 250m, and temporal step for the seeding cases is considered to be 1 second, and 5 seconds for the no-seeding case.

Model initial and boundary conditions

The present modified model uses the same initial and boundary conditions as those of Pirhayati (2010) model. For the model, the upper air data such as temperature, relative humidity, dew point temperature and hydrostatic pressure are used as functions of height. The atmosphere around the cloud in the model has a temperature lapse rate (denoted Γ_d) of 6.3C°/km. However, from 10 km above the ground surface onwards, the temperature remains constant at the same value as 10 km level from the ground has reached to. In addition, the temperature and relative humidity at the ground surface are assumed 25C° and 100 percent, respectively. The relative humidity decreases at a rate of 5 percent per km from the ground level up. This model is initiated using upper air data which were calculated during previous steps of model. According to the sounding data, the freezing level is found to be at a height of 4.25km from the ground. During the seeding simulation, can be adjusted, mixing ratio of the seeding agent, height, time and temperature of the seeding, and also the cloud thickness and CTL of the no-seeded cloud. For this model, motion in the environmental atmosphere is initiated by introducing a small updraft that has the form

$$W_{t=0}=\Delta w(z/z_0)(2-(z/z_0)), \tag{1}$$

where this formulation is for the layer below 2km where Δw=1m/s and z_0=1km.

The boundary conditions used here are the ground level and a height of 15 km from the ground. For these two levels, the vertical velocity (w), cloud water mixing ratio (Q_c), rainwater mixing ratio (Q_r), cloud ice mixing ratio (Q_i), snow mixing ratio (Q_s), and hail/graupel mixing ratio (Q_G) are assumed to be zero. Moreover, temperature (T) and water vapor mixing ratio (Q_v) are kept constant in these two levels.

Ice nuclei equation

Since the Fletcher (1962) equation for the ice nuclei somehow over estimates the ice-crystal concentrations in the very cold clouds, and since this equation is not supposedly sensitive to the saturation conditions, therefore combination of the Fletcher and the Huffman equations[20,21] conducted by Cotton et al.(1986) is implemented in this study .The Cotton equation is as follows:

$$N_{id}=n_0[(S_i-1)/(S_0-1)]^b\exp(\beta_1\Delta T), \tag{2}$$

where, $\beta_1=0.6^{o}C^{-1}$, b=4.5, $n_o= 10^{-5}$ li $^{-1}$. Also here ΔT is the degree of super-cooling, S_i-1 is the ice super-saturation ratio, and S_o-1 is the ice super-saturation ratio at saturated water.

Since, the activity of ice nuclei (IN) depends on both the super-saturation ratios and temperature [1]. The present study, uses Cotton equation for IN, in which both the super-saturation ratios and temperature are taken into account. It should be mentioned that in the previous seeding investigation, this issue didn't considered.

Modal governing equations

The dynamical and microphysical equations of the present model like those of Pirhayati (2010) model are based on modified Ogura Takashi's cloud model [18] and lin et al [16], respectively. In the present study, the terms of glaciogenic seeding processes due to homogenous agent (LCO_2) are added to the cloud model according to the models by Hise et al.(1980) and Guo et al.(2006). Moreover, in the present work, heterogeneous ice nucleation is based on the Cotton et al. (1986). The appropriate mass, momentum, and energy conservation equations, are used for all the hydrometeors considered in this model. Due to the existence of the turbulent flow within the considered cloud model, all the variables are divided into the average and perturbation quantities. It is noted that the average quantities are determined with respect to the cloud surface cross section [22]. The simplification for the variables in the governing equations are made based on the dimensional reasoning (considering the order of magnitude of the effective terms), and the Boussinesq approximation. It should be noted that Boussinesq approximation limits the effects of the density arrangement only to the buoyancy force within the governing equations. In this study, the cloud is modeled in the cylindrical coordinates (r , θ , z). It is assumed that the pressure at any cloud altitude takes the same value as that of the environment in hydrostatic equilibrium. In addition, drag forces are provided by the weight of liquid and solid water .Since cloud model is assumed axi symmetric, in the governing equations, ($\frac{\partial}{\partial\theta}$) is set equal to zero.

For the present model, the appropriate continuity, momentum and energy governing equations, and also the conservation equations of hydrometeor mixing ratios, respectively become,

$$\frac{1}{r}\frac{\partial}{\partial r}\left(\rho_{a0}ru\right)+\frac{\partial}{\partial z}\left(\rho_{a0}w\right)=0 \tag{3}$$

$$\rho_{a0}\frac{\partial w}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}\left(\rho_{a0}ruw\right)+\frac{\partial}{\partial z}\left(\rho_{a0}ww\right)=\rho_{a0}g\left(\frac{T-T_{v0}}{T_{v0}}\right)+F_{Drag} \tag{4}$$

$$\frac{\partial T}{\partial t}=-w\left(\frac{\partial T}{\partial z}-\Gamma_d\right)+\frac{2\alpha^2}{a}|w|(T_0-T)+\frac{2}{a}\tilde{u}_a\left(T-\widetilde{T}_a\right)+\left(\frac{L_v}{C_P}\right)(\text{processes in the line of evaporation})+\left(\frac{L_s}{C_P}\right)(\text{processes in the line of sublimation})+\left(\frac{L_f}{C_P}\right)(\text{processes in the line of freezing})-\frac{\partial X_s}{\partial t}\left(T-T_{sco_2}\right)-\frac{L_{co_2}}{c_v}\frac{\partial X_s}{\partial t} \tag{5}$$

$$\frac{\partial Q_r}{\partial t} = -(\mathrm{w} - V_{\mathrm{w}})\frac{\partial Q_r}{\partial z} + Q_r\frac{\partial(\rho_{a0}V_{\mathrm{w}})}{\rho_{a0}\partial z} + \frac{2\alpha^2}{a}|\mathrm{w}|\left(Q_{r_0} - Q_r\right) + \frac{2}{a}\tilde{u}_a\left(Q_r - \tilde{Q}_{ra}\right) + \text{sources} - \text{sinks} \tag{6}$$

$$\frac{\partial Q_s}{\partial t} = -(\mathrm{w} - V_{s})\frac{\partial Q_s}{\partial z} + Q_s\frac{\partial(\rho_{a0}V_{s})}{\rho_{a0}\partial z} + \frac{2\alpha^2}{a}|\mathrm{w}|\left(Q_{s_0} - Q_s\right) + \frac{2}{a}\tilde{u}_a\left(Q_s - \tilde{Q}_{sa}\right) + \text{sources} - \text{sinks} \tag{7}$$

$$\frac{\partial Q_G}{\partial t} = -(\mathrm{w} - V_{G})\frac{\partial Q_G}{\partial z} + Q_G\frac{\partial(\rho_{a0}V_{G})}{\rho_{a0}\partial z} + \frac{2\alpha^2}{a}|\mathrm{w}|\left(Q_{G_0} - Q_G\right) + \frac{2}{a}\tilde{u}_a\left(Q_G - \tilde{Q}_{Ga}\right) + \text{sources} - \text{sinks} \tag{8}$$

$$\frac{\partial Q_i}{\partial t} = -\mathrm{w}\frac{\partial Q_i}{\partial z} + \frac{2\alpha^2}{a}|\mathrm{w}|\left(Q_{i_0} - Q_i\right) + \frac{2}{a}\tilde{u}_a\left(Q_i - \tilde{Q}_{ia}\right) + \text{sources} - \text{sinks} \tag{9}$$

$$\frac{\partial Q_c}{\partial t} = -\mathrm{w}\frac{\partial Q_c}{\partial z} + \frac{2\alpha^2}{a}|\mathrm{w}|\left(Q_{c_0} - Q_c\right) + \frac{2}{a}\tilde{u}_a\left(Q_c - \tilde{Q}_{ca}\right) + \text{sources} - \text{sinks} \tag{10}$$

Where, in these equations, the subscript zero and "a" denote the quantities in the environment and at the air column radius, respectively. Also, "ρ", "u" , " w" , and T_v are air density, radial, and vertical velocities, virtual temperature, respectively.

Conservation equation of seeding agent and modified energy equation by glaciogenic seeding (LCO_2) are as follows:

$$\frac{\partial X_S}{\partial t} = -\mathrm{w}\frac{\partial X_S}{\partial Z} - \frac{2\alpha^2}{a}|\mathrm{w}|(X_S) + \frac{2}{a}\tilde{u}_a\left(X_S - \tilde{X}_S\right) \tag{11}$$

$$\frac{\partial T}{\partial t} = -\mathrm{w}\left(\frac{\partial T}{\partial z} - \Gamma_d\right) + \frac{2\alpha^2}{a}|\mathrm{w}|(T_0 - T) + \frac{2}{a}\tilde{u}_a\left(T - \tilde{T}_a\right) + \left(\frac{L_v}{C_P}\right)(P_{COND} - P_{CLEVP} - P_{REVP}) + \left(\frac{L_s}{C_P}\right)(-P_{IEVP} + P_{NUA} + P_{IDEP} - P_{SSUB} - P_{GSUB} + P_{SDEP}) + \left(\frac{L_f}{C_P}\right)(-P_{IMLT} + P_{SFW} + P_{IACRS} + P_{SACRS} + P_{SACW} - P_{SMLT} + P_{GFR} + P_{GACW} + P_{GACR} + P_{SACRG} + P_{IACRG} - P_{GMLT} + P_{NUH} + P_{NUF} + P_{ISR} + P_{CSWC} + P_{CSWD}) - \frac{\partial X_s}{\partial t}\left(T - T_{sco_2}\right) - \frac{L_{co_2}}{c_v}\frac{\partial X_s}{\partial t} \tag{12}$$

Where in the aforementioned equations " X_S" , " $\tilde{u}_a$" , " α^2", and "a" are indicative of seeding agent, entrainment or detrainment velocity, and lateral perturbation which is considered equal to *0.1* , and radius of air column, respectively. In the energy equation (Eq.12), Γ_d, L_v, L_s, L_f , and c_v=717 J/(kg.K) are the dry adiabatic lapse rate, latent heat of evaporation (600cal/g), sublimation (680cal/g), fusion (80cal/g), and heat capacity at constant volume for the dry air, respectively. Moreover, in the equation the vaporization latent heat and the surface temperature of seeding agent are L_{co_2}=55 cal/g and $T_{sco_2} = -90C°$, respectively.

Due to LCO_2 seeding, some new terms are added to the thermodynamic (energy) equation which are resulted from the cooling and heating processes. The cooling processes are due to vaporization of liquid and heat conduction between the seeded air and the LCO_2 droplets. The heating processes are due to the accretion of super-cooled liquid water by ice crystals and vapor deposition on ice particles both of which are formed by the seeding agent.

The microphysical and dynamical processes calculations include many judgments such as $T \gtreqless 273C°$, $Q_v \gtreqless Q_{vs}$, $Q_v \gtreqless Q_{is}$, $Q_{is} < Q_v < Q_{vs}$, $Q_r \gtreqless 0$, $Q_G \gtreqless 0$, and $Q_s \gtreqless 0$.

The Cumulonimbus cloud and its life cycle stages

The hypothetical model of single cell convective cloud contains three stages of developing, mature, and dissipation. In the developing stage, there is strong climbing thermal, in which the speed of updraft flow increases quickly with the height. At the same time, entrainment emerges in the side boarders of the cloud. Moreover the cloud top is moving upward and the cloud is growing with an acceptable rate. Although there is no precipitation in this stage, there are hydrometeors inside the cloud. In the mature stage, the cloud extends continuously until the cloud height reach neutral buoyancy level. In this stage, a strong downdraft flow which is overlapped with the intense rainfall and it is retained with the drag force caused by the weight of hydrometeors. Evaporation cooling is also created in unsaturated air of the cloud and entrainment of air in the side boarders of the cloud leads to negative buoyancy in the air of downdraft flow. Maximum vertical speeds generally occur on the top of the level of detrainment area. In this stage, rainfall begins and both upward and downward flows are in the cloud. Downward motion is created by the evaporative cooling resulted from separated precipitation from upward motion, so the area of maximum downward motion is in a height lower than the area of maximum upward motion. Inversion at the cloud top due to heat entrainment creates an area of negative temperature differences. After a while, downdraft motions extended horizontally and occupies a huge part of the cloud . At this time, the stage of dissipation begins and precipitation stops. In this stage the downdraft motion is the dominant motion in the cloud and at the end of this stage, cloud will disappear due to evaporation [23,24].

RESULTS AND DISCUSSIONS

In this study, a lot of sensitivity tests on the seeding conditions are carried out for achieving more details on the glaciogenic seeding effects due to homogenous agent. Sensitivity of rainfall enhancement and hydrometers mixing ratios to different cases, including no-seeding, point seeding, and horizontal seeding are analyzed. These analyses are done for clouds with different CTL and thickness. In order to evaluate sensitivity of seeding effects (rainfall enhancement and hail suppression) to different CTL and different cloud thickness, upper air data are adjusted in which, clouds with different thickness and CTLs are formed. Afterwards, these clouds are seeded with different methods. In addition, sensitivity of rainfall enhancement to the seeding time and seeding positions (at the top, middle, and base of the cloud) for two clouds are studied. For achieving these aims, two deep convective cloud with CTL=10.5, 7km are selected for analyses. The cloud with CTL=7km , which is common cloud in tropical regions where have severe problems due to the water shortage [25] and the cloud with CTL=10.5km, which is a mixed cloud. Sensitivity of microphysical processes and hydrometeors mixing ratios to the seeding in different conditions and their effects on precipitation are demonstrated for aforementioned clouds. It should be mentioned that, vertical extension of mixed cloud increases due to the seeding and it's CTL is equal to 11km after seeding.

Sensitivity of rainfall to seeding method and CTL

As shown in Fig.1, rainfall on the ground is sensitive to seeding methods (different modes of releasing seeding agent) and CTL of clouds. One the one hand, rainfall due to the point seeding is more than horizontal seeding in the clouds with CTL more than 7km. On the other hand, horizontal seeding is more effective method for rainfall enhancement in the clouds with CTL less than 8 km. The reason may refer to the different kinds of clouds in which clouds with CTL more than 8km are mixed clouds. Rainfall enhancement, depending on the CTL and seeding method varies from 1% to 52% .

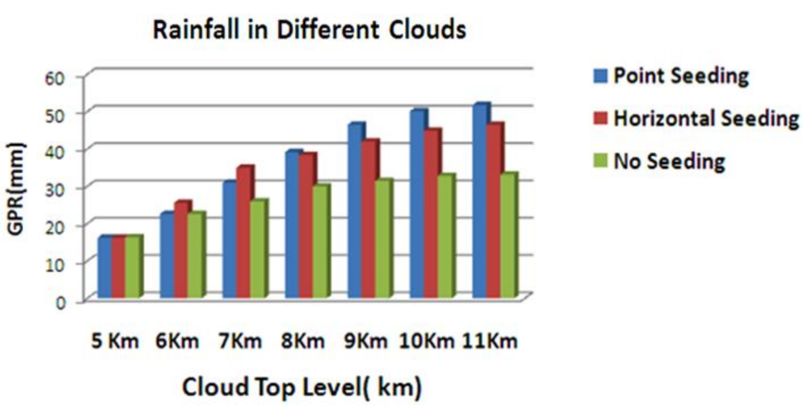


Fig.1: Rainfall on the ground in different cases vs. cloud top level

Changes of hydrometeors mixing ratios

As shown in Fig.2, on the one hand, percentage of rainwater mixing ratio due to the seeding in the clouds with CTL less than 8 km increases in both seeding cases, on the other hand, hail/graupel mixing ratio of these clouds decreases after seeding specially in the point seeding case. hail/graupel mixing ratio in the clouds with CTL more than 7km increases. Therefore, glaciogenic cloud seeding with homogenous seeding agent (LCO_2) is effective for the aims of hail suppersion and rainfall enhancement for clouds with CTL less than 8km.

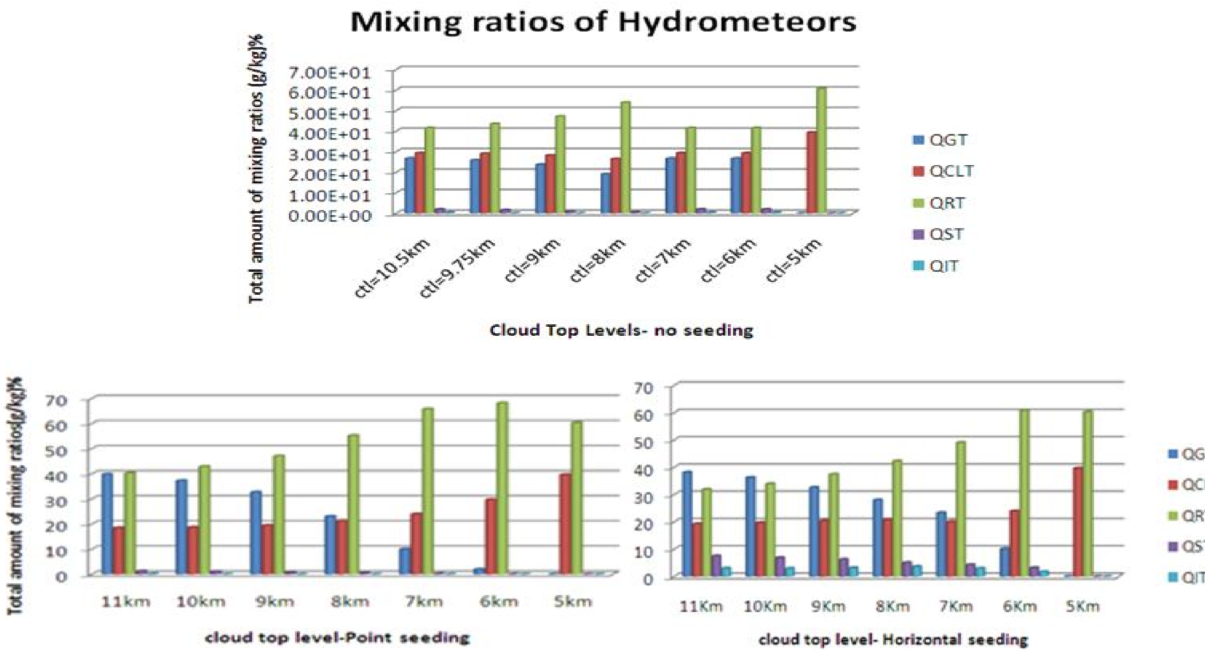
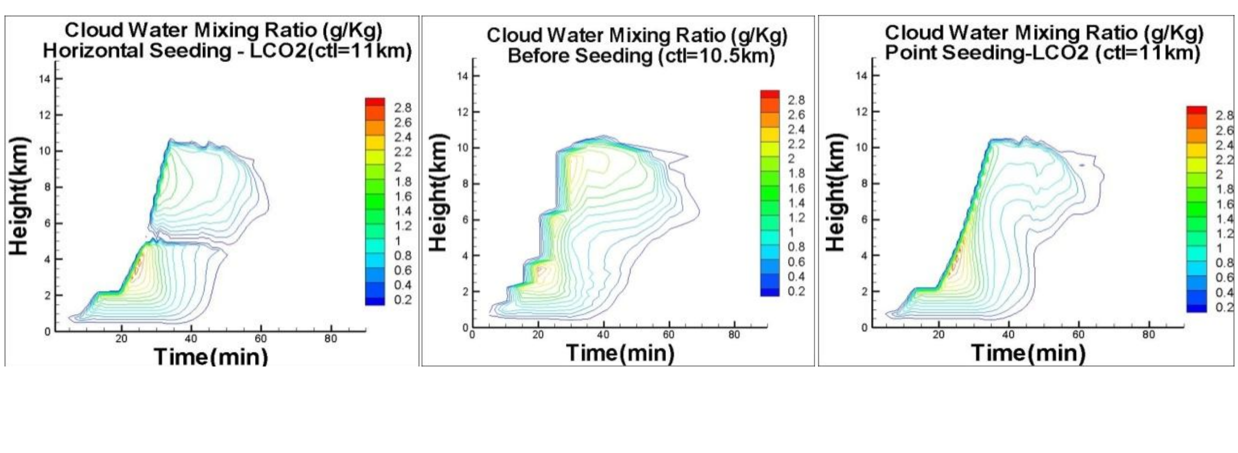
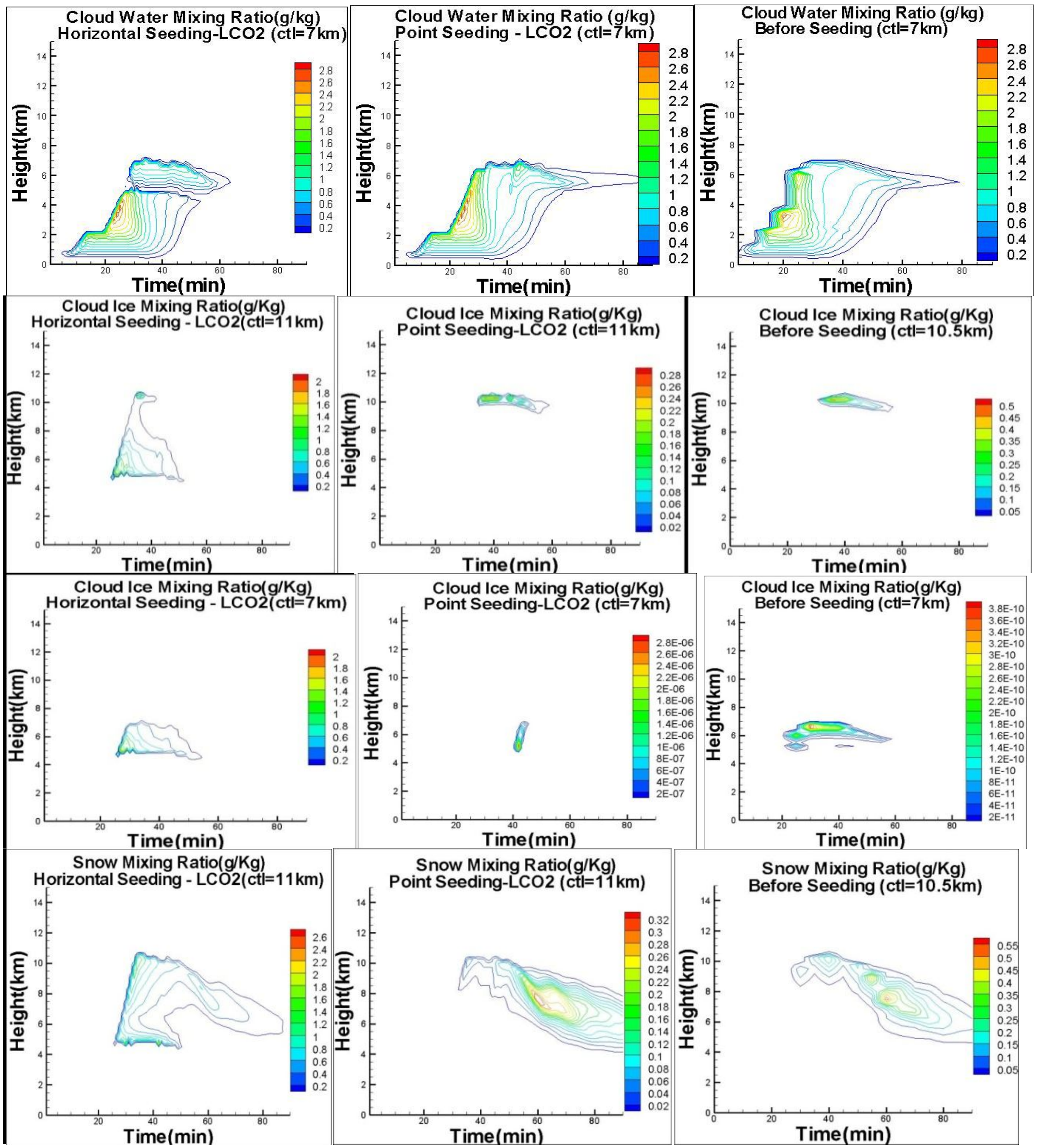


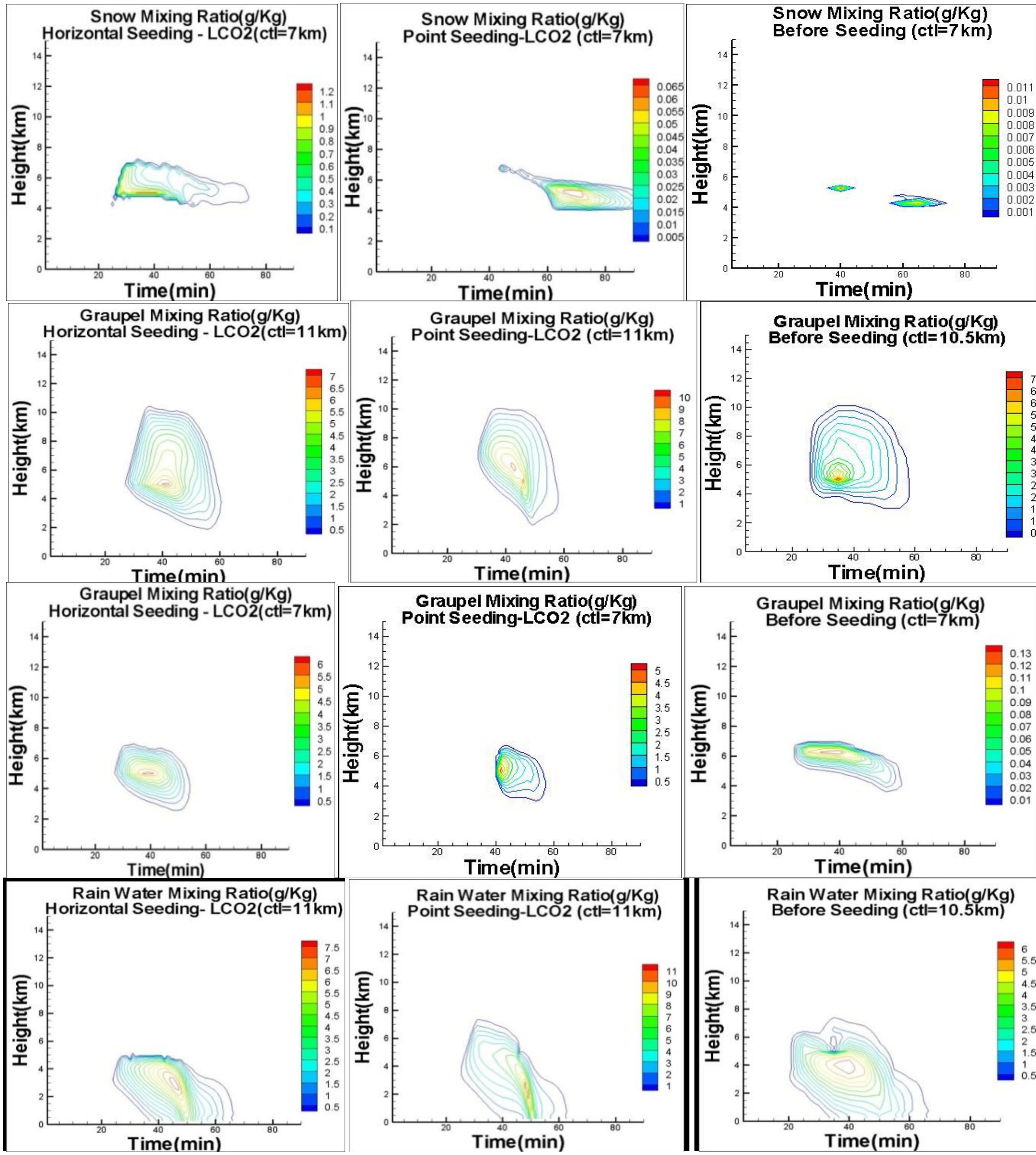
Fig.2: Total amount of hydrometeors mixing ratio% vs. clouds with different CTL

Hydrometeors mixing ratios in the clouds with different thickness and seeding methods

The processes relevant to depletion of cloud water (liquid water) include the supercooled cloud water accretion by hail/graupel (P_{GACW}), snow (P_{SACW}) and rain (P_{RACW}), freezing (P_{NUH}/ P_{NUA}/P_{NUF}), evaporation (P_{CLEVP}), natural Bergeron-Findisen process (P_{SFW}), artificial Bergeron-Findisen process (P_{CSWD}) due to the deposition on the seeding [13], and depositional growth of cloud ice in expense of cloud water (P_{IDEP})[16]. As shown in the cloud water plots of Fig.3, the cloud water depletion in one layer of cloud is obvious in the horizontal seeding case. Results of numerical analyses show, the reason of this phenomenon is, severe homogeneous nucleation resulted from Bergeron-Findisen process due to seeding agent and consequently sudden decrease in temperature. As shown in the plots of cloud water and cloud ice mixing ratios, an ice layer is produced due to the cloud water depletion. In other words, the consumption of cloud water and the transformation of the cloud water into snow in a level, which is a bit higher than freezing level results in cloud water depletion in that level (Fig.3). All cases have a cloud water peak near 5 km. Thus, it can be seen an increase of cloud water with height below this level. The cloud water is closely related to the ascending motion and exhibits a tri-center pattern in the no-seeding case and dual-center pattern in the seeding cases [26].




Cloud Water Mixing Ratio(g/kg)
Horizontal Seeding-LCO2 (ctl=7km)
Cloud Water Mixing Ratio (g/kg)
Point Seeding - LCO2 (ctl=7km)
Cloud Water Mixing Ratio (g/kg)
Before Seeding (ctl=7km)
Cloud Ice Mixing Ratio(g/Kg)
Horizontal Seeding - LCO2(ctl=11km)
Cloud Ice Mixing Ratio(g/Kg)
Point Seeding-LCO2 (ctl=11km)
Cloud Ice Mixing Ratio(g/Kg)
Before Seeding (ctl=10.5km)
Cloud Ice Mixing Ratio(g/Kg)
Horizontal Seeding - LCO2(ctl=7km)
Cloud Ice Mixing Ratio(g/Kg)
Point Seeding-LCO2 (ctl=7km)
Cloud Ice Mixing Ratio(g/Kg)
Before Seeding (ctl=7km)
Snow Mixing Ratio(g/Kg)
Horizontal Seeding - LCO2(ctl=11km)
Snow Mixing Ratio(g/Kg)
Point Seeding-LCO2 (ctl=11km)
Snow Mixing Ratio(g/Kg)
Before Seeding (ctl=10.5km)
Height(km)
Time(min)


Snow Mixing Ratio(g/Kg)
Horizontal Seeding - LCO2(ctl=7km)
Snow Mixing Ratio(g/Kg)
Point Seeding-LCO2 (ctl=7km)
Snow Mixing Ratio(g/Kg)
Before Seeding (ctl=7km)
Graupel Mixing Ratio(g/Kg)
Horizontal Seeding - LCO2(ctl=11km)
Graupel Mixing Ratio(g/Kg)
Point Seeding-LCO2 (ctl=11km)
Graupel Mixing Ratio(g/Kg)
Before Seeding (ctl=10.5km)
Graupel Mixing Ratio(g/Kg)
Horizontal Seeding - LCO2(ctl=7km)
Graupel Mixing Ratio(g/Kg)
Point Seeding-LCO2 (ctl=7km)
Graupel Mixing Ratio(g/Kg)
Before Seeding (ctl=7km)
Rain Water Mixing Ratio(g/Kg)
Horizontal Seeding- LCO2(ctl=11km)
Rain Water Mixing Ratio(g/Kg)
Point Seeding-LCO2 (ctl=11km)
Rain Water Mixing Ratio(g/Kg)
Before Seeding (ctl=10.5km)
Height(km)
Time(min)

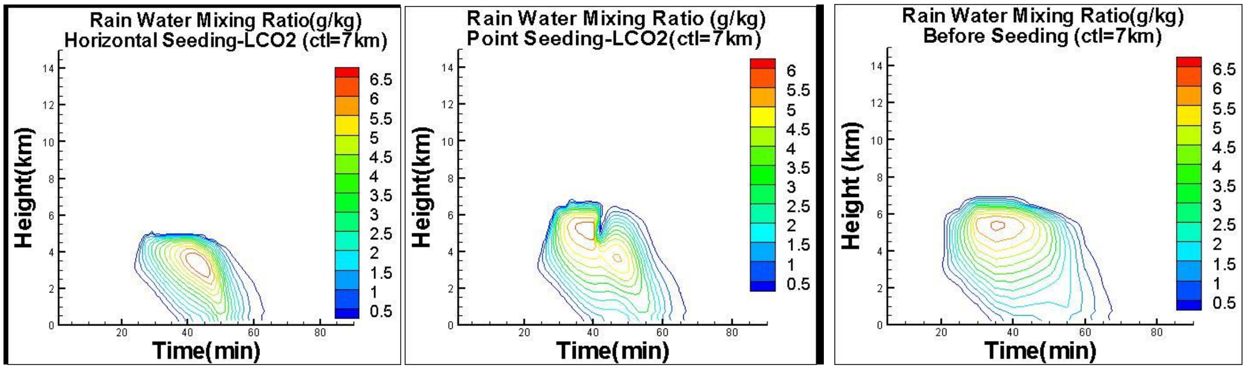


Fig.3: Height vs. Time plots of hydrometeors mixing ratio

Although many clouds reside partially or completely above freezing level, cloud water does not freeze instantaneously as they are exposed to negative temperatures. These clouds can exist in a metastable super cooled condition for a long time [1]. As shown in the cloud ice mixing ratio plots, in the no-seeding cases, the cloud with CTL= 10.5Km is a mixed cloud and has significant amount of ice crystals. At the same time, the cloud ice amount in the cloud with CTL=7Km is negligible. Due to the lower equilibrium vapor pressure of ice as compared to liquid, ice crystals in mixed clouds grow at the expense of the cloud droplets (Bergeron-Findisen process, [27]. In the horizontal seeding case, maximum amount is at least 4 times more than no-seeding case. It should be mentioned that in the horizontal seeding, cloud ice, which is produced in the height of 5 Km (approximately 1Km higher than freezing level) decreases upward. In this case, severe and continues cooling made by homogenous seeding , decreases ice concentration in the high altitudes. In the cloud with (CTL=7km) cloud top doesn't reach high altitudes and ice formation is negligible in this cloud.

Snow can be formed by the Bergeron–Findisen processes (P_{SFI}, P_{SFW}) and auto conversion of cloud ice to snow (P_{SAUT}), various accretion terms (collisions of snow with cloud ice (P_{SACI}), cloud water(P_{SACW}), and hail/graupel(P_{SACG})), three component freezing terms such as P_{SACRG}, P_{SACRS}, snow melting(P_{SMLT}) , sublimation(P_{SSUB}) , and deposition(P_{SDEP}). As shown in the plots of snow mixing ratio of Fig.3, maximum amount of snow mixing ratio in the horizontal seeding case is at least 5 times more than other cases. It should be mentioned that in the mixed cloud (CTL=10.5km), snow is formed at the end of developing stage and in the low altitude (5km) . However, in the point seeding case and no-seeding one, maximum amount of snow is achieved in the beginning of mature stage and in the high altitudes. This phenomenon in the mixed cloud, which creates snow sooner, can be due to the existence of significant amount of ice crystals in the horizontal seeding case. The vertical extension of snow mixing ratio is due to large temperature difference between the seeding agent (-90C°) and seeding temperature (-1C°) resulting from the horizontal and continuous seeding. In the horizontal seeding case, further snow content is produced because of more contact nucleation, cloud water accretion and secondary freezing due to the seeding. At the same time, sensible heat which is released due to cloud water accretion increases the snow melting.

As shown in the graupel mixing ratios plots of Fig.3, distribution of the hail/graupel mixing ratio in the mixed cloud indicates the maximum amount in the early mature stage in the height of 5 Km (a bit higher than freezing level). In the point seeding case, hail/graupel vertical extension increases and temporal distribution of that decreases. In the horizontal seeding, the region with the maximum amount of hail/graupel is more extended than other cases. The maximum amount of hail/graupel mixing ratio in the point seeding, horizontal seeding and no-seeding cases reduces. There is a significant decrease in temporal distribution of hail/graupel in the point seeding case. In all cases, there is a reduction in the distribution of hail/graupel mixing ratio with decreases the cloud thickness and cloud top height (Fig.3). The reason for this reduction may refer to the different initial amount of ice concentration in these clouds.

As shown in the rain water mixing ratios plots of Fig.3, the eye wall and rain band are formed below freezing level in the mixed cloud seeding cases. On the one hand, the maximum amount of rain mixing ratio increases due to the seeding and on the other hand, temporal distribution of that decreases. Difference of temporal distribution of rain mixing ratio is obvious for two types of cloud, and eye wall area in the cumulus cloud with CTL=7km is boarder than mixed cloud. This is due to less amount of hail/graupel in this cloud. The rain water and cloud water are mostly found below the freezing level while other ice-phase particles are mostly seen above it and the melting of snow and hail/graupel affects the growth of rain water mainly in the spiral rain bands. This is according to Rui *et al.* (2010) in their work. Ice processes played a significant role in the development of precipitation, and rain resulted primarily from graupel particles produced by riming which is in agreement with Yin *et al*. (1999), [28]. Franklin *et al*. (2005) found that graupel particles would be mostly restricted at the inner core of thunderstorm [29]. This can be seen in the plots of rain water and hail/graupel mixing ratios of Fig.3.

Sensitivity tests on seeding time and positions

Study of seeding effects sensitivity to seeding time and positions is one of the most important goals of the present work. For achieving this goal, both clouds are seeded at the beginning of developing, mature, and dissipation stages of cloud lif cycle and after that seeding effects are studied. The results show the most rainfall (at least 2 mm more than other stages) due to seeding in the early mature stage. It was intresting point that, just seeding effects at this stage (mature stage) were sensitive to the seeding positions (top, middle and base of the cloud).Therefore, all the sensitivity tests for seeding positions in this work are carried out for the seeding in the early mature stage of cloud life cycle.

Sensitivity of rainfall and rainfall intensity to the seeding positions

Sensitivity of rainfall on the ground to the seeding positions is shown for two clouds(Fig.). As shown in Fig.4, the most rainfall ocurrs when the seeding is carried out at the middle of the cloud. Lowest amount of rainfall is produced for the mixed cloud and the cloud with CTL=7km, duo to seeding at the base and top of the cloud, respectively. As shown in the Fig.5, rainfall intensity of mixed cloud is more sensitive than cloud with CTL=7km. Peak of rainfall intensity duo to the seeding at the top of the cloud is approximately twice of that for seeding at base of the cloud in the mixed cloud. Based on the seeding goals, target reaion features, and plots of rainfall and rainfall intensity for the clouds, appropraite seeding position can be selected.

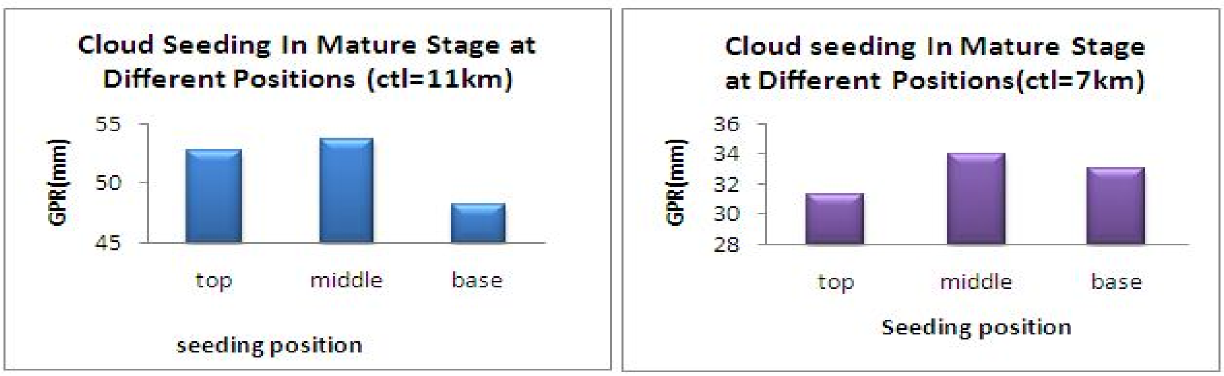


Fig. 4: Rainfall on the ground vs. Seeding positions

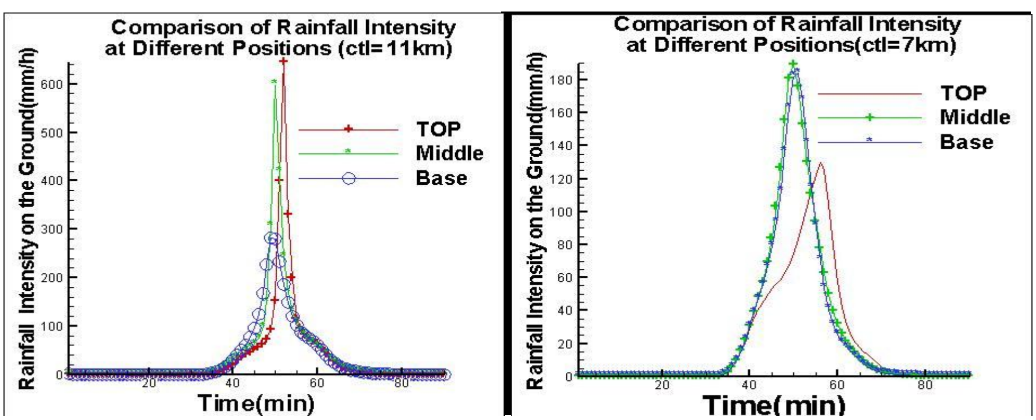


Fig.5: Rainfall intensity on the ground vs. Time

Sensitivity of hydrometeors mixing ratio to seeding locations

Figure 6 shows percentage of hydrometeors mixing ratios with respect to different seeding locations (seeding at base, middle, and top of the cloud). As shown in the figure, cloud seeding in the cloud with CTL=7km with the aims of hail suppression and rainfall enhancement can be effective, when the seeding operation occurs at the top of the cloud. Cloud seeding in the mixed cloud with CTL=11km should be done at the base of the cloud with the aim rainfall enhancement and also hail suppression . As it can be seen in Figures . 2,5,6 for this mixed cloud, the seeding increases nearly 10% hail production with respect to no-seeding case, but it should be noticed that, seeding at suitable position can reduce amount of rainfall intensity and hail fall enhancement which are partly dangerous for some regions.

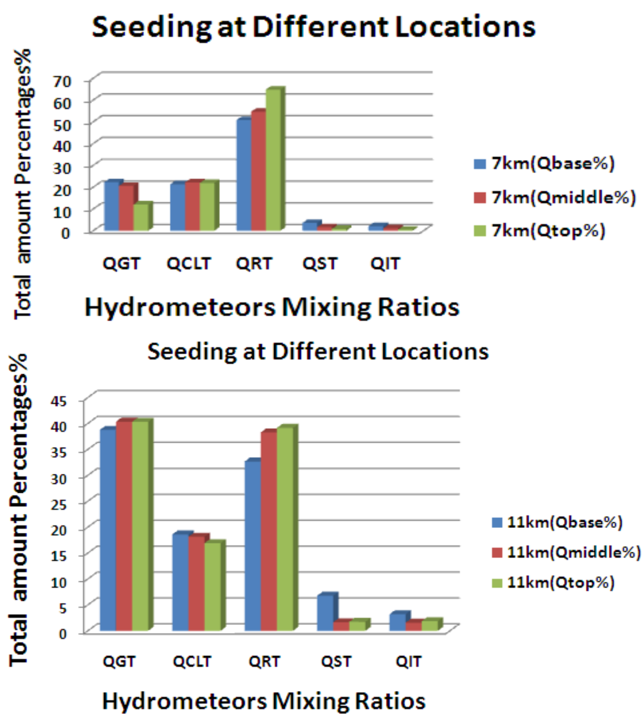
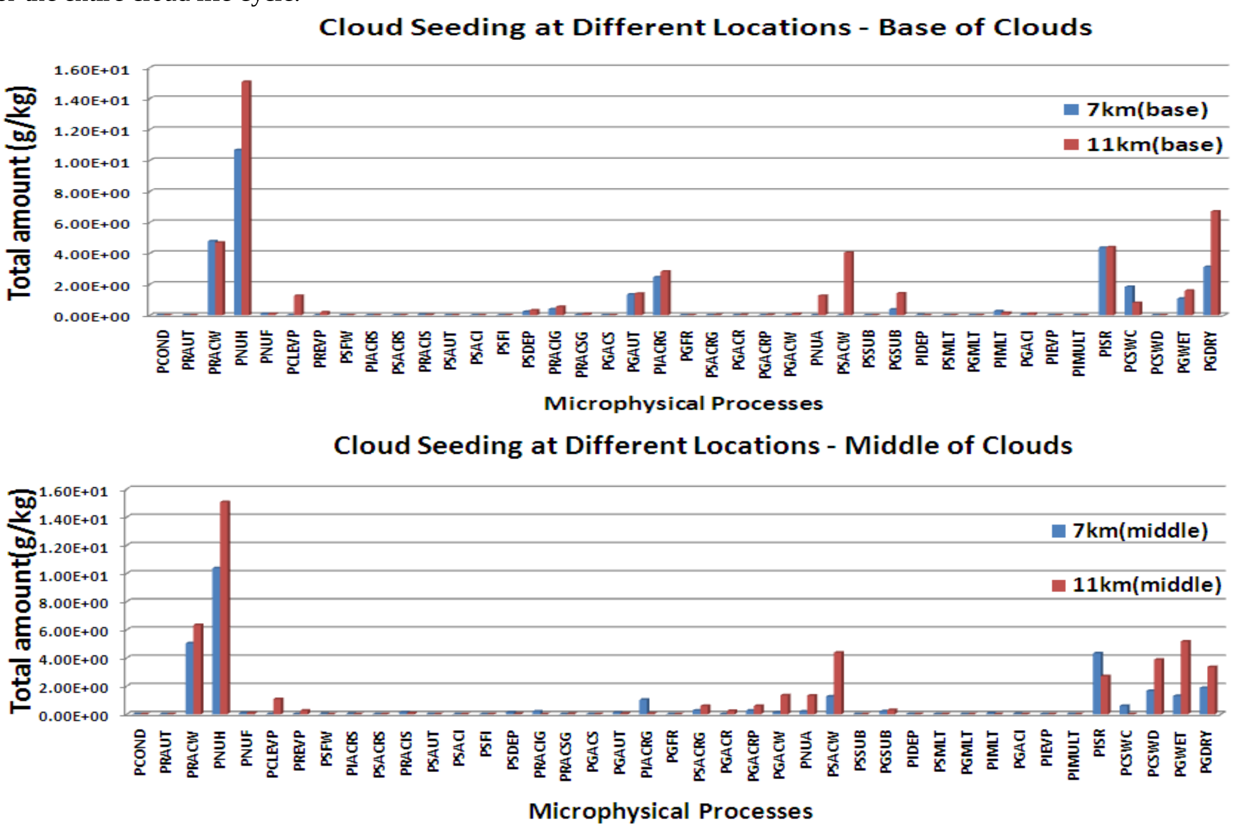


Fig.6: Percentage of hydrometeors mixing ratios in the cloud life cycle

Sensitivity of microphysical processes to seeding locations

Effects of seeding locations on microphysical processes are illustrate for the mixed cloud and cloud with CTL=7km in the following figures. It shoud be mentioned that total amount of microphysical processes are obtained for the entire cloud life cycle.



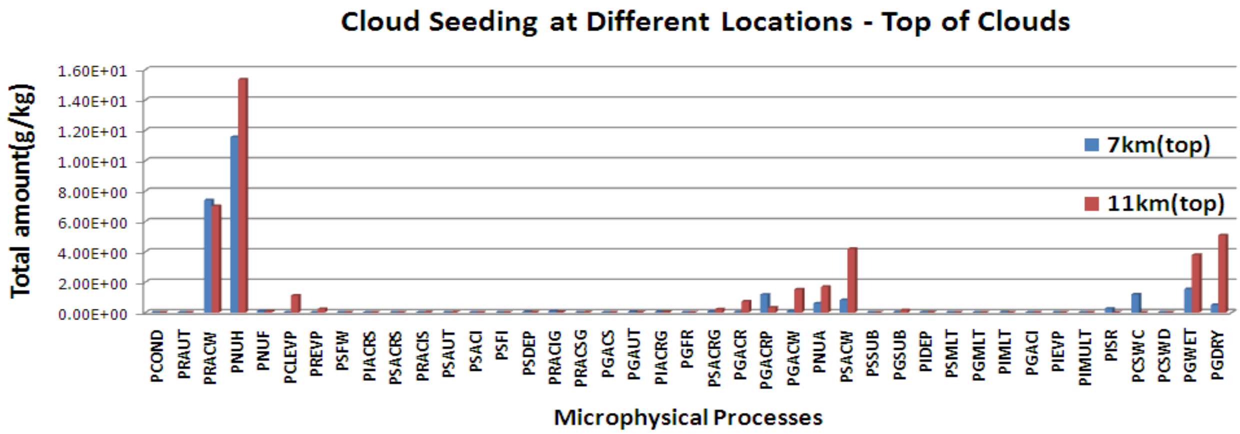


Fig. 7: Effects of seeding locations on microphysical processes

According to Fig.7 , in all cases (seeding at top, middle and base of clouds) the most effective processes are homogeneous nucleation (P_{NUH}) and after that, cloud water accretion by the rain water (P_{RACW}). Homogeneous freezing of cloud water and rain occurs instantaneously at temperatures below -40°C. Although homogeneous ice nucleation is possible in any super cooled water drop, nucleation rates are negligibly small at temperatures warmer than approximately -30C [1]. The glaciogenic seeding with homogenous seeding agent, coolant agent, increases nucleation rate partly. For this reason, homogeneous freezing is the dominant process in the formation of deep convective clouds which are seeded. This kind of seeding, modifies cloud conditions like cirrus clouds which form at temperatures below about -35 C naturally and in tops of deep cumulus forming within a smoky air with a high CCN concentration [1].

The difference between clouds and seeding positions affect the amount of seeding process activation and temporal distribution of their activity and some processes which are activated according to the threshold limit e.g. wet and dry growth of hail/graupel (P_{GWET} , P_{GDRY}) and three component freezing and accretion processes. In the high altitudes, clouds arrive to some levels which there can be formed ice crystals because of low temperature in those regions. This phenomenon causes accretion of cloud water by snow (P_{SACW}) in the mixed cloud. In all cases, by increasing height of seeding location, activity of cloud water accretion by the rain water (P_{RACW}) increases and transformation of rainwater to precipitating ice (P_{ISR}) and sublimation of hail/graupel (P_{GSUB}) decreases (Fig.7).

Conclusions

In this study, numerical analysis of homogeneous cloud seeding agent (LCO_2) is carried out for deep convective clouds in which one of them is a mixed cloud. Numerical analysis is conducted to evaluate the role of homogenous seeding agent on the rainfall enhancement and hail/graupel production in convective clouds. The sensitivity of seeding effects to seeding methods(different modes of releasing seeding agent), seeding time (stage of cloud life cycle) , seeding position (seeding at the top, middle, and base of the cloud) , and cloud top level (CTL) also was tested.

For achieving aforementioned goals, upper air data are adjusted in which clouds with different top level can formed. Afterwards, Sensitivity of rainfall and hydrometeors mixing ratio to seeding methods, seeding time (seeding at the beginning of developing, mature, and dissipation stages) are studied. Moreover, sensitivity of rainfall , rainfall intensity, and hail/graupel production to the seeding positions and cloud top level in two clouds in which one of them is a mixed cloud are analyzed.

The results of analyses with respect to seeding time show that cloud seeding in the early mature stage of the cloud life cycle creates the most rainfall enhancement. Sensitivity of seeding effects to seeding positions can be seen just for the seeding in the mature stage (Figs.4,5,6,7). The results of sensitivity tests show that, point seeding and horizontal seeding are effective seeding method for the clouds with CTL more and less than 8km, respectively. It was also found that, depending on the CTL and seeding method , rainfall enhancement can vary from 1% to 52% (Fig.1). It is distinguished that rainfall of clouds with higher CTL is larger. The reason is that, convective motions and heat transfer increase with cloud thickness. The updraft motions on cloud droplets near the cloud base are slow but, as the cloud thickness increase, the updraft velocity increase with the instability augmentation due to release of cloud water and seeding agent latent heat. Therefore, heat transfer of cloud water, and convective available potential energy and consequently rainfall will be increased [30]. Numerical analysis confirms the sensitivity of hydrometeors mixing ratios to different seeding method and CTL(Fig.2). The results also show the cloud water depletion in one layer of cloud in the horizontal seeding case due to severe homogeneous nucleation resulted from Bergeron-Findisen process due to seeding agent and consequently sudden decrease in temperature (Fig.3).All cases have a cloud water peak near 5 km. The cloud water is closely related to the ascending motion and exhibits a tri-center pattern in the no-seeding case and dual-center pattern in the seeding cases [26]. The numerical analysis indicate, in the point seeding case and no-seeding one, maximum amount of snow is achieved in the beginning of mature stage and in the high altitudes. This phenomena in the mixed cloud, which creates snow sooner, can be due to the existence of significant amount of ice crystals in the horizontal seeding case. The vertical extension of snow mixing ratio is due to large temperature difference between the seeding agent (-90C°) and seeding temperature (-1C°) resulting from the horizontal and continuous seeding. The rain water and cloud water are mostly found below the freezing level while other ice-phase particles are mostly seen above it and the melting of snow and hail/graupel affects the growth of rain water mainly in the spiral rain bands. This is according to Rui *et al.* (2010) in their work. Ice processes played a significant role in the development of precipitation, and rain resulted primarily from graupel particles produced by riming which is in agreement with Yin *et al.* (1999). Franklin *et al.* (2005) found that graupel particles would be mostly restricted at the inner core of thunderstorm.

Sensitivity of rainfall and rainfall intensity to the seeding positions show the most rainfall ocurrs when the seeding is carried out at the middle of the cloud. Peak of rainfall intensity duo to the seeding at the top of the cloud is approximately twice of that for seeding at base of the cloud in the mixed cloud. Based on the seeding goals, target reaion features, and plots of rainfall and rainfall intensity for the clouds, appropraite seeding position can be selected. Numerical analysis on the sensitivity of microphysical proceeses to seeding position show that the most effective processes in all positions are homogeneous nucleation (P_{NUH}) and cloud water accretion by the rain water (P_{RACW}). The difference between clouds and seeding positions affect the amount of seeding process activation and temporal distribution of their activity and some processes which are activated according to the threshold limit e.g. wet and dry growth of hail/graupel (P_{GWET} , P_{GDRY}) and three component freezing and accretion processes. Activity of ice processes which are dependent on the ice nuclei can differ by changing cloud top level and are very important in the rainfall (Fig.7) .

It should be mentioned that , the precipitation amount of the model and its maximum precipitation intensity is highly in correspondence with the results of empirical observations [31].

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Appendix

List of Symbols

Notation	Description
a	Radius of air column which is considered equal to *3* km
$\tilde{A}$	Lateral boundary average value of the cloud such as $\widetilde{Q}$, $\tilde{T}$
$\tilde{u}_a$	Entrainment or detrainment velocity (m/s)
L_{co_2}	vaporization latent heat (55 cal/g)
T_{sco_2}	Surface temperature of seeding agent ($-90C°$)
X_S	Seeding agent mixing ratio(g/kg)

α^2 Lateral perturbation which is considered equal to *0.1*
c_v Heat capacity at constant volume for the dry air(717 J/(kg.K))
L_v, L_s, L_f Latent heat of evaporation (600cal/g),sublimation (680cal/g) , and fusion (80cal/g)
PCOND Production rate for condensation(g $kg^{-1}s^{-1}$)
PCSWC Production rate of cloud ice due to contact nucleation of seeding agent and cloud water (g $kg^{-1}s^{-1}$).
PCSWD Production rate of cloud ice result in artificial Bergeron-Findisen process (deposition on the seeding agent)(g $kg^{-1}s^{-1}$)
PGACI Production rate for accretion of cloud ice by graupel (g $kg^{-1}s^{-1}$)
PGACR Production rate for accretion of Rain by graupel (g $kg^{-1}s^{-1}$)
PGACS Production rate for accretion of snow by graupel (g $kg^{-1}s^{-1}$)
PGACW Production rate for accretion of cloud water by graupel (g $kg^{-1}s^{-1}$)
PGAUT Production rate for autoconversion of snow to form graupel (g $kg^{-1}s^{-1}$)
PGDRY Dry growth of graupel; involves PGACS, PGACI, PGACW and PGACR. (g $kg^{-1}s^{-1}$)
PGFR Probabilistic freezing of rain to form graupel (g $kg^{-1}s^{-1}$)
PGMLT Production rate for graupel melting to form rain, $T \geq T_0$ (g $kg^{-1}s^{-1}$).
PGSUB Production rate for graupel sublimation (g $kg^{-1}s^{-1}$)
PGWET Wet growth of graupel (g $kg^{-1}s^{-1}$)
PRACI Production rate for accretion of cloud ice by rain (g $kg^{-1}s^{-1}$)
PIACRS/PIACRG three component processes result in hydrometeors accretion which cause cloud ice production (g $kg^{-1}s^{-1}$)
PIDEP Production rate for depositional growth of cloud ice at expense of cloud water (g $kg^{-1}s^{-1}$)
PIMLT Production rate for melting of cloud ice to form cloud water (g $kg^{-1}s^{-1}$)
PISR Transformation rate of rainwater to precipitating ice due to seeding (g $kg^{-1}s^{-1}$)
PJEVP Production rate for J= cloud water (CL), rain(R), cloud Ice (I) evaporation (g $kg^{-1}s^{-1}$)
PNUA Production rates of cloud ice by using ice nuclei (g $kg^{-1}s^{-1}$)
PNUH Production rates for homogenous freezing of cloud water($\Delta T \geq 40$) to form cloud ice (g $kg^{-1}s^{-1}$)
PNUF Production rates for freezing of cloud water($\Delta T \leq 40$) to form cloud ice (g $kg^{-1}s^{-1}$)
PRACSG/PRACIG/PRACIS Three component processes result in hydrometeors accretion which cause rain production(g $kg^{-1}s^{-1}$)
PRACW Production rate for accretion of cloud water by rain (g $kg^{-1}s^{-1}$)
PRAUT Production rate for autoconversion of cloud water to form rain
PSACI Production rate for accretion of cloud ice by snow (g $kg^{-1}s^{-1}$)
PSACRS Three component processes result in hydrometeors accretion which cause snow production (g $kg^{-1}s^{-1}$)
PSACW Production rate for accretion of cloud water by snow (g $kg^{-1}s^{-1}$)
PSDEP Production rate for depositional growth of snow (g $kg^{-1}s^{-1}$)
PSFI Transfer rate of cloud ice to snow through growth of Bergeron Process embryos (g $kg^{-1}s^{-1}$)
PSFW Production rate for Bergeron Process-transfer of cloud water to form snow (g $kg^{-1}s^{-1}$)
PSMLT Production rate for snow melting to form rain (g $kg^{-1}s^{-1}$)
PSSUB Production rate for sublimation of snow (g $kg^{-1}s^{-1}$)
Q_j Mixing ratio(g/kg) of cloud water(C), Rain (r), ice (i), Hail/Graupel (G), Snow (s), vapor(v) , J=c,r,i,G,s
S_i-1 Ice super-saturation ratio
S_o-1 Ice super-saturation ratio at saturated water.
T, T_v Temperature, virtual temperature in which T_v=T (1+0.608 Q_r)
u ,w Radial and vertical velocity (m/s), respectively.
V_j Mass-weighted mean terminal velocity(m/s) of j=Rain(R) ,Graupel(G), and Snow(S)
β_1, b, n_o Constants in the Ice nuclei equation β_1=0.6$^o C^{-1}$, b=4.5, n_o= 10^{-5} li^{-1}
Γd Dry adiabatic lapse rate
ΔT Degree of super-cooling
ρ air density (g/cm^3)