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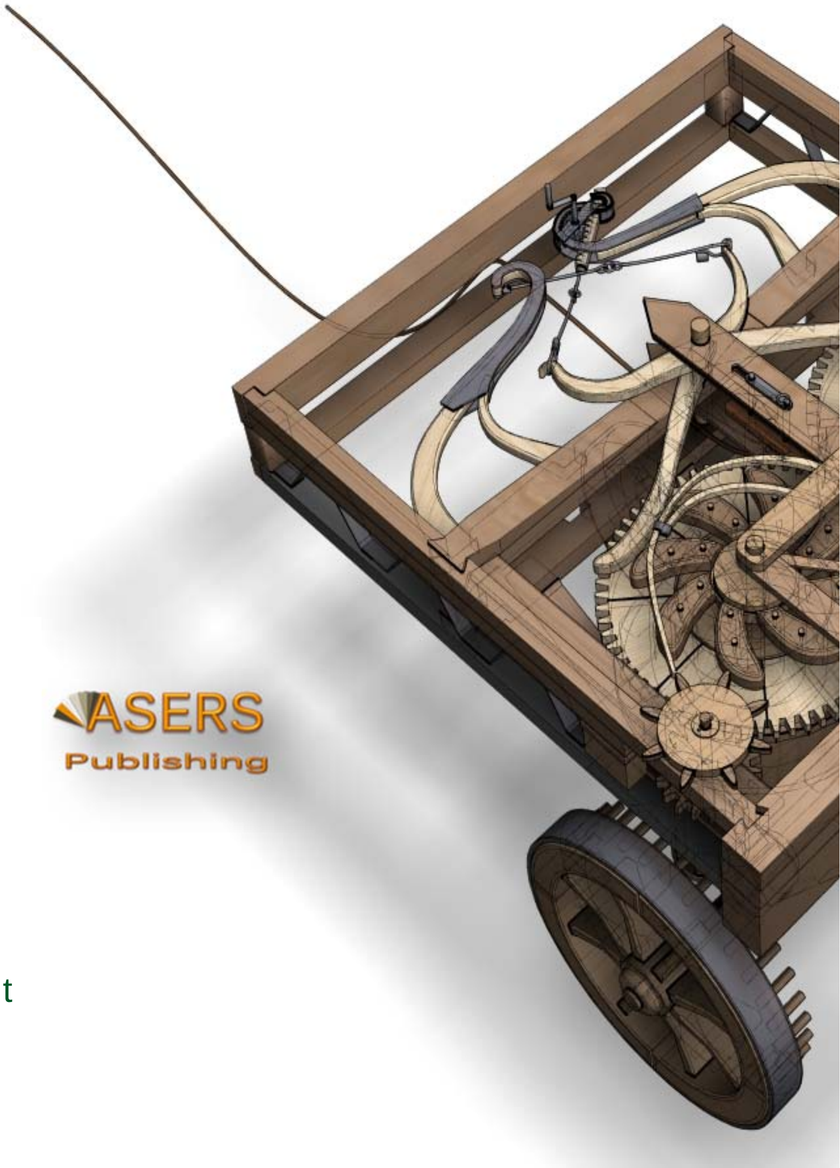

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Mathematical Modeling of Formation of Transparency Regions in Supercooled Stratiform Clouds and Fogs

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Abstract:

We developed models of active influence on clouds using crystallization reagents to ensure transparency of the atmosphere. Numerical modeling of various versions of influence on stratiform clouds at aviation seeding was performed. Variation of characteristics of supercooled fogs when bringing man-made crystals was studied. The determination of reagents application rates, estimating impact effect and some other issues were solved using the results of modelling of clouds evolution (both natural and under active influence). Based on generalization of the results of numerical simulation of cloud evolution, the proposals for improvement of cloud seeding technology under different weather conditions are developed.

Keywords: stratiform clouds; numerical models; transparency regions; crystallization reagent; microphysical processes; snow; rain.

JEL Classification: Q56; F64

Introduction

The problems of dissipation of clouds and fogs were and still remain topical. During time, their urgency increases. Now these problems become of particular importance in connection with appearance of high-speed vehicles as well as development of laser and other technologies. Both cloudiness and fogs hinder solution of many economic and other problems. To solve them, it is necessary to perform further theoretical and experimental researches on physics of formation and evolution of various clouds and fogs as well as on active influence (AI) on them (Ashabokov and Shapovalov 2008, Bakhanov *et al.* 1990, Bakhanov and Kolezhuk 1990, Bekryaev 1991, Beryulev *et al.* 1996, Denis 1983, Kachurin 1990, Methodical instructions 1999, Pirnach 1990, Polovina 1980, Chernikov *et al.* 1999, Hindman and Johnson 1972, Stefanov and Calovski 2003).

As means of reagent delivery to clouds and fogs, spray generators (ground or installed on aircraft side) are used, as well as pyrocartridges sending from Earth or airplane, various ground or airplane dosing plants, shells, rockets, etc. (depending on the object of influence - cloud or fog). At present silver iodide, dry ice and liquid nitrogen are the most widespread crystallizing reagents used for AI on supercooled clouds (Denis 1983, Kachurin 1990, Methodological instructions 1999, Polovina 1980, Krasnovskaya *et al.* 1987, Mazin and Shmeeter 1983).

Bringing of silver iodide crystals from an airplane into clouds is made in two ways:

- by spraying below the cloud bottom or directly into the clouds at the heights where ice-forming efficiency is sufficiently high or maximal; in this case dispersion is made by burning the reagent acetone solution in a special burner;
- by shooting pyrocartridges at the cloud tops; the pyrocartridges are burning in the course of falling through the cloud depth and release a big amount of silver iodide crystals into supercooled cloud volume.

To process big areas, a dosed drop of granular dry ice from an airplane is used. In recent years the ice particle generators (spraying liquid nitrogen in a cloud) have extensive application for seeding stratiform clouds. Such nitrogen technology is simple, economic and highly reliable, as well as ecologically safe.

An adaptation of the methods of AI on clouds to requirements of different kinds of activity as well as adjustment of the operating guides need performance of further in-depth investigations in this line, with wide application of mathematical modeling based on the modern models. Our work deals with the problems of mathematical modeling of formation of transparency regions in supercooled clouds and fogs. We used the improved as well as newly developed models for theoretical investigations of various aspects of the problem of AI on clouds. These are the model of microphysical processes in stratiform clouds and 2D model of convective cloud (with detailed regard for thermodynamic and microphysical processes in them), 3D model of convective cloud (Ashabokov and Shapovalov 2008, Kogan *et al.* 1984), etc. The atmospheric sounding data in the territories of Stavropol krai and Kabardino-Balkarskaya Republic (characteristic of the four seasons) served as the starting parameters.

1. Modeling of thermodynamic parameters of cloudy atmosphere

We used a model with a set of hydrothermodynamic equations that were applied for numerical modeling in (Ashabokov and Shapovalov 2008, Bakhanov *et al.* 1990, Bakhanov and Kolezhuk 1980, Bekryaev 1991, Denis 1983, Kachurin 1990, Methodical instructions 1988, Mazin and Shmeeter 1983, Khvorostyanov 1988, Khvorostyanov 1986). The hydrothermodynamic set of the model involves the equations of motion describing moist convection in the Boussinesq approximation, with allowance made for advective and turbulent transport as well as forces of buoyancy, friction and barometric gradients (Mazin and Shmeeter 1983):

$$\frac{\partial u}{\partial t}+\left(\vec{V}\cdot\nabla\right)u=-\frac{\partial\pi'}{\partial x}+\Delta' u+lv\,, \tag{1}$$

$$\frac{\partial v}{\partial t}+\left(\vec{V}\cdot\nabla\right)v=-\frac{\partial\pi'}{\partial y}+\Delta' v-lu\,, \tag{2}$$

$$\frac{\partial w}{\partial t}+\left(\vec{V}\cdot\nabla\right)w=-\frac{\partial\pi'}{\partial z}+\Delta' w+g\left(\theta'/\theta_0+0.61s'-Q_S\right), \tag{3}$$

equations of continuity

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=\sigma w,\qquad \sigma=\frac{d\ln\rho_0(z)}{dz}\,, \tag{4}$$

and thermodynamic equations

$$\frac{\partial\theta}{\partial t}+\left(\vec{V}\cdot\nabla\right)\theta=\frac{L_C}{C_p}\frac{\theta}{T}\frac{\delta M_C}{\delta t}+\frac{L_S}{C_p}\frac{\theta}{T}\frac{\delta M_S}{\delta t}+\frac{L_F}{C_p}\frac{\theta}{T}\frac{\delta M_F}{\delta t}+\Delta'\theta\,, \tag{5}$$

$$\frac{\partial s}{\partial t}+\left(\vec{V}\cdot\nabla\right)s=-\frac{\delta M_C}{\delta t}-\frac{\delta M_S}{\delta t}+\Delta' s\,. \tag{6}$$

Here

$$\left(\vec{V}\cdot\nabla\right)\equiv u\frac{\partial}{\partial x}+v\frac{\partial}{\partial y}+w\frac{\partial}{\partial z},\qquad \Delta'=\frac{\partial}{\partial x}K\frac{\partial}{\partial x}+\frac{\partial}{\partial y}K\frac{\partial}{\partial y}+\frac{\partial}{\partial z}K\frac{\partial}{\partial z}, \tag{7}$$

where: $\vec{V}=\{u,v,w\}$ is velocity vector;

$u(\vec{r})$, $v(\vec{r})$ and $w(\vec{r})$ are components of the velocity vector for air flows in a cloud;

$(\vec{r})$ is potential temperature;

$(\vec{r})=c_p\,\overline{\theta}\,(p(\vec{r})/1000)^{R/Cp}$ is dimensionless pressure;

$\overline{\theta}$ is average potential temperature;

R is gas constant;

$s(\vec{r})$ is specific humidity of air;

$Q_S(\vec{r})$ is cumulative ratio of a mixture of liquid and solid phases in a cloud;

σ (z) is parameter accounting for air density changing with height;

$P(\vec{r})$ and $T(\vec{r})$ are pressure and temperature, respectively;

C_p is heat capacity of air at constant pressure;

L_C, L_S and L_F are specific heat of condensation, sublimation and freezing, respectively;

$'(\vec{r})$, $\theta'(\vec{r})$ and $s'(\vec{r})$ are deviations of dimensionless pressure, potential temperature and specific humidity, respectively, from their background values $\pi_b(\vec{r})$, $\theta_b(\vec{r})$ and $s_b(\vec{r})$ in the ambience;

$\frac{\delta M_C}{\delta t}$ and $\frac{\delta M_S}{\delta t}$ are changes of specific humidity (due to diffusion of vapor onto drops and crystals, respectively);

$\frac{\delta M_F}{\delta t}$ is mass of condensed water freezing per unit air volume per unit time;

$K(\vec{r})$ is coefficient of turbulent diffusion. The vector $\vec{r}$ corresponds to the coordinates (x, y, z). The symbols 0, L_x, 0, L_y and 0, L_z are used for the boundaries of the spatial domain.

The initial and boundary conditions for the set of Equation (1)–(3) are as follows:

$$u(\vec{r},0)=u^0(\vec{r}), \tag{8}$$

$$v(\vec{r},0)=v^0(\vec{r}), \tag{9}$$

$$w(\vec{r},0)=w^0(\vec{r}), \tag{10}$$

$$\theta(\vec{r},0)=\theta^0(\vec{r}), \tag{11}$$

$$u=u_0(z),\quad \theta=\theta_0(z),\quad p=p_0(z),\quad q=q_0(z)\ \text{at}\ x=0,L_x, \tag{12}$$

$$v=v_0(z),\quad \theta=\theta_0(z),\quad p=p_0(z),\quad q=q_0(z)\ \text{at}\ y=0,L_y, \tag{13}$$

$$u=v=w=0,\quad \theta=\theta_0(0),\quad p=p_0(0),\quad q=q_0(0)\ \text{at}\ z=0, \tag{14}$$

$$u=u(L_z),\quad v=v(L_z),\quad w=0,\quad \theta=\theta_0(L_z),\quad p=p_0(L_z),\quad q=q_0(L_z)\ \text{at}\ z=L_z. \tag{15}$$

2. Modeling of microphysical processes in clouds

The microphysical set describes the processes of nucleation, condensation, drop-drop coagulation, sublimation, accretion, drop freezing, precipitation of cloud particles in the gravity field and transfer of them by air flows, as well as interaction of cloud particles under the influence of cloud electric field. A set of equations for drops, ice particles and frozen drop fragments mass distribution functions ($f_1(\vec{r},m,t)$, $f_2(\vec{r},m,t)$ and $f_3(\vec{r},m,t)$, respectively) is such (Ashabokov and Shapovalov 2008):

$$\frac{\partial f_1}{\partial t}+u\frac{\partial f_1}{\partial x}+v\frac{\partial f_1}{\partial y}+(w-V_1)\frac{\partial f_1}{\partial z}=\left(\frac{\partial f_1}{\partial t}\right)_{cond.}+\left(\frac{\partial f_1}{\partial t}\right)_{coag.}+\left(\frac{\partial f_1}{\partial t}\right)_{acc.}+\left(\frac{\partial f_1}{\partial t}\right)_{break.}+\left(\frac{\partial f_1}{\partial t}\right)_{freez.}+\Delta' f_1+I_1,$$

$$\frac{\partial f_2}{\partial t}+u\frac{\partial f_2}{\partial x}+v\frac{\partial f_2}{\partial y}+(w-V_2)\frac{\partial f_2}{\partial z}=\left(\frac{\partial f_2}{\partial t}\right)_{subl.}+\left(\frac{\partial f_2}{\partial t}\right)_{acc.}+\left(\frac{\partial f_2}{\partial t}\right)_{freez.}+\Delta' f_2+I_2+I_{AB}, \tag{16}$$

$$\frac{\partial f_3}{\partial t}+u\frac{\partial f_3}{\partial x}+v\frac{\partial f_3}{\partial y}+(w-V_2)\frac{\partial f_3}{\partial z}=\left(\frac{\partial f_3}{\partial t}\right)_{freez.}+\left(\frac{\partial f_3}{\partial t}\right)_{acc.}+\Delta' f_3.$$

where: V_1(m) and V_2(m) are steady rates of fall of liquid and solid particles, respectively;

$\left(\frac{\partial f_1}{\partial t}\right)_{cond.}$, $\left(\frac{\partial f_1}{\partial t}\right)_{coag.}$, $\left(\frac{\partial f_1}{\partial t}\right)_{acc.}$, $\left(\frac{\partial f_1}{\partial t}\right)_{break.}$ and $\left(\frac{\partial f_1}{\partial t}\right)_{freez.}$ are changes of drop distribution function owing to microphysical processes of drop condensation, drop coagulation, accretion of drops and crystals, fragmentation and freezing, respectively;

$\left(\frac{\partial f_2}{\partial t}\right)_{subl.}$, $\left(\frac{\partial f_2}{\partial t}\right)_{acc.}$ and $\left(\frac{\partial f_2}{\partial t}\right)_{freez.}$ are changes of crystal distribution function owing to sublimation, accretion and freezing of drops, respectively;

$\left(\frac{\partial f_3}{\partial t}\right)_{freez.}$ and $\left(\frac{\partial f_3}{\partial t}\right)_{acc.}$ are changes of distribution function $f_3(\vec{r},m,t)$ owing to fragments formation at spontaneous freezing of cloud drops and accretion, respectively.

The following initial and boundary conditions are used for the set of Equation (1):

$$f_1(\vec{r},m,0)=f_2(\vec{r},m,0)=f_3(\vec{r},m,0)=0, \tag{17}$$

$$f_1(\vec{r},m,t)=f_2(\vec{r},m,t)=f_3(\vec{r},m,t)=0 \text{ at } x=0,L_x,. \tag{18}$$

$$f_1(\vec{r},m,t)=f_2(\vec{r},m,t)=f_3(\vec{r},m,t)=0 \text{ at } y=0,L_y,. \tag{19}$$

$$f_1(\vec{r},m,t)=f_2(\vec{r},m,t)=f_3(\vec{r},m,t)=0 \text{ at } z=L_z, \tag{20}$$

$$\frac{\partial f_1}{\partial z}=\frac{\partial f_2}{\partial z}=\frac{\partial f_3}{\partial z}=0 \text{ at } z=0. \tag{21}$$

To describe coagulation processes in a cloud, the following integro-differential equation is used (Kogan *et al.* 1984):

$$\begin{aligned}\left(\frac{\partial f}{\partial t}\right)_{coag.}&=-f_1(\vec{r},m,t)\int_0^{\infty}\beta_1(m,m')\cdot f_1(\vec{r},m',t)dm'+\\&+\int_0^{m/2}f_1(\vec{r},m-m',t)\beta_1(m,m-m')f_1(\vec{r},m',t)dm',\end{aligned} \tag{22}$$

where: $\beta_1(m,m')=\pi(r(m)+r(m'))^2\cdot\left|V_1(m)-V_1(m')\right|\cdot E_1(m,m')$;

$r(m)$ and $r(m')$ are radii of colliding particles;

$V_1(m)$ and $V_1(m')$ are their rates of fall;

$E_1(m, m')$ is coefficient of drop trapping.

The linear impact factor for drops of radii r<400μm is calculated from the approximating expression (Khvorostyanov 1986)

$$E_1=1+P_1-A_1\cdot P_1^{-C_1}-B_1\cdot(1-P_1)^{-D_1}, \tag{23}$$

where: $P_1= r/r'$;

$A_1 = 27.2\, r^{-1.645}$;

$B_1= 58.5\, r^{-1.9}$;

$C_1 = (15.24/r)^4 + 1.13;$

$D_1 = (16.65/r)^8 + 0.00393\, r' + 0.98.$

The impact factor for drops of big radii r_i>400μm is determined from the limiting formula:

$$E_1 = 1 + P_1. \qquad (24)$$

The interaction of drops and crystals is calculated using the following relations:

$$\left(\frac{\partial f_1}{\partial t}\right)_{acc.} = -f_1(\vec{r},m,t)\int_0^\infty \beta_2(m,m')\cdot f_2(\vec{r},m',t)dm' \qquad (25)$$

$$\left(\frac{\partial f_2}{\partial t}\right)_{acc.} = -f_2(\vec{r},m,t)\int_0^\infty \beta_2(m,m')\cdot f_1(\vec{r},m',t)dm' + \qquad (26)$$

$$+\int_0^m \beta_2(m,m-m')f_2(\vec{r},m-m',t)f_1(\vec{r},m',t)dm',$$

where: $\beta_2(m,m') = \pi(r(m)+r(m'))^2\cdot\left|V_1(m)-V_2(m')\right|\cdot E_2(m,m'),$

E_2 is trapping coefficient for drops and crystals. It is supposed that collisions between crystals and drops lead to drops freezing (Ashabokov and Shapovalov 2008).

3. Some results of numerical experiments

Based on the developed model, we performed numerical experiments on cloud seeding with reagents to ensure transparency of the atmosphere under adverse weather conditions (presence of clouds or fog). The data for atmospheric sounding are given in Table 1.

Table 1. The data of aerological sounding

H(m)	P (mbar)	T (°C)	T_d (°C)	dT_{dd} (°C)	V (m/s)	Alfa (deg)
1000	920	5.0	2.6	2.4	2	360
2000	811	-1.0	-3.3	2.3	1	300
3000	713	-5.0	-7.2	2.2	4	330
4000	626	-11.0	-13.1	2.1	5	260
5000	547	-18.0	-20.0	2.0	4	220
6000	477	-22.0	-23.8	1.8	25	80
7000	415	-30.0	-31.7	1.7	15	220
8000	358	-38.0	-39.6	1.6	14	210
9000	308	-48.0	-49.5	1.5	13	210

Notation: *H*(m) - height above sea level, *P*(mbar) - atmospheric pressure, *T*(°C) - air temperature, T_d(°C) - dew point temperature, dT_{dd}(°C) - dew point deficit; *V*(m/s) - horizontal wind speed; Alfa (deg) - wind direction.

The results of analysis of atmospheric condition from the sounding data are given in Table 2. The thermodynamic parameters at the lower and upper cloudiness boundaries are as follows: lower cloudiness boundary = 1600 m; temperature at the lower boundary = 1.4 °C; pressure at the lower boundary = 856 mbar; upper cloudiness boundary = 3100 m; temperature at the upper boundary = –5.6 °C; wind speed = 4.1 m/s; wind direction is 323 deg.

Table 2. Water vapor in the atmosphere

SI	Height (m)	Water vapor pressure (mbar)	Mass fraction of water vapor (g per kg of air)	Pressure of saturated water vapor (mbar)	Absolute humidity (g/m³)	Relative humidity (%)
1	1000	7.36	4.99	8.72	5.75	84.4
2	2000	4.79	3.68	5.68	3.82	84.4
3	3000	3.56	3.11	4.21	2.88	84.5
4	4000	2.23	2.22	2.64	1.85	84.5

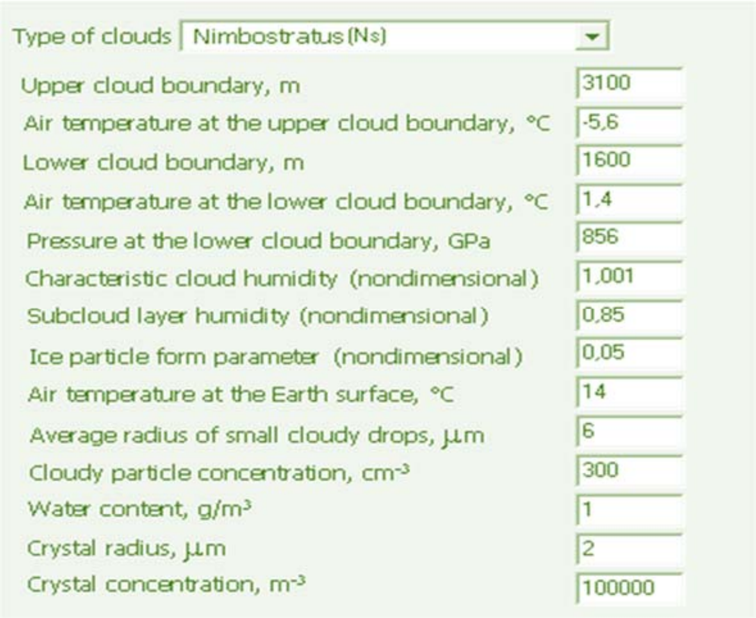
SI	Height (m)	Water vapor pressure (mbar)	Mass fraction of water vapor (g per kg of air)	Pressure of saturated water vapor (mbar)	Absolute humidity (g/m^3)	Relative humidity (%)
5	5000	1.25	1.43	1.49	1.07	84.3
6	6000	0.90	1.17	1.05	0.78	85.3
7	7000	0.43	0.65	0.51	0.39	85.0
8	8000	0.20	0.34	0.23	0.18	84.8
9	9000	0.07	0.13	0.08	0.06	84.3

When analyzing atmosphere, we determined the character heights that are required at performance of AI with a crystallizing reagent (see Table 3). A version of the initial data at modeling AI is given in Figure 1.

Table 3. Typical heights in the atmosphere

Temperature (°C)	Height (m)	Temperature (°C)	Height (m)
0	1830	-15	4570
-6	3170	-25	6380
-10	3830	-40	8200

Figure 1. Characteristics of cloudiness



Type of clouds	Nimbostratus (Ns)
Upper cloud boundary, m	3100
Air temperature at the upper cloud boundary, °C	-5,6
Lower cloud boundary, m	1600
Air temperature at the lower cloud boundary, °C	1,4
Pressure at the lower cloud boundary, GPa	856
Characteristic cloud humidity (nondimensional)	1,001
Subcloud layer humidity (nondimensional)	0,85
Ice particle form parameter (nondimensional)	0,05
Air temperature at the Earth surface, °C	14
Average radius of small cloudy drops, µm	6
Cloudy particle concentration, cm^{-3}	300
Water content, g/m^3	1
Crystal radius, µm	2
Crystal concentration, m^{-3}	100000

From the results of calculations, we determined the man-made crystal growth time at supercooled clouds dissipation by seeding with a crystallizing reagent (Krasnogorskaya 1965). The initial data of the version were as follows:

Air (cloud) temperature *t* (°C) = –5.6
Air pressure *P* (mbar) = 850
Cloud water content Q (g/m^3) = 1.00
Average radius of cloud drops RW0 (µm) = 6.0
Concentration of cloud drops NW0 (1/m^3) = 300000000
Visible range before influence L0 (m) = 57
Radius of man-made crystals RL0 (µm) = 2.0
Concentration of ice particles (1/m^3) = 100000.
The result of modeling showed that crystal growth time = 960 s (16 min).

Let us consider the results of modeling precipitate particle growth in stratiform clouds. The initial data were as follows:

height of the upper cloud boundary over the Earth = 3100 m
temperature at the upper cloud boundary = 267.55 K

height of the lower cloud boundary over the Earth = 1600 m
temperature at the lower cloud boundary = 274.55 K
pressure at the lower cloud boundary = 856.0 mbar
average radius of small cloud drops = 0.000006 m
characteristic cloud humidity = 1.00100
humidity in the subcloud layer = 0.85
ice particle shape parameter = 0.0500
air temperature near the Earth surface = 287.15 K
particle radius R = 89.1 μm.

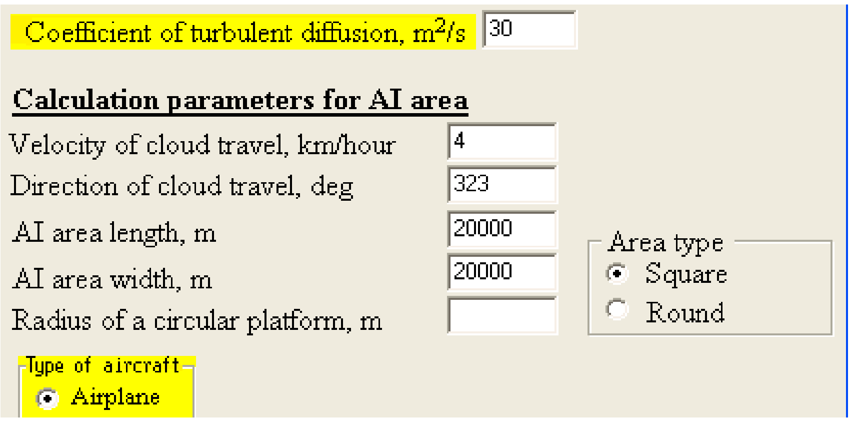
The results of calculations of action of small ice crystals at the upper boundary of stratiform clouds showed that their radius increases as small ice crystals are sinking. The crystal growth time, equivalent radius and position in a cloud are given in Table 4. The precipitation formation time was 1070 s (18 min).

Table 4. Results of calculations on particle growth

Height Z (m)	Time TAU (s)	Equivalent ice particle radius R_{eq} (m)
3050	0.0	0.000089
2950	97.1	0.000098
2850	193.9	0.000107
2750	290.1	0.000118
2650	385.9	0.000130
2550	481.1	0.000145
2450	575.6	0.000162
2350	669.3	0.000183
2250	762.0	0.000206
2150	853.8	0.000233
2050	944.6	0.000261
1950	1034.3	0.000289
1900	1069.9	0.000302

Let us consider the results of modeling formation of a square (20×20 km) window region. The coefficient of turbulent diffusion and seeding area parameters are given in Figure 2, while the calculated values of reagent consumption are given in the lower line of Figure 3. The calculated covering time for a big square (20×20 km) transparency region with coefficient of turbulent diffusion K = 30 m^2/s was 240 min (4 hours).

Figure 2. AI area parameters



Coefficient of turbulent diffusion, m²/s: 30

Calculation parameters for AI area

Velocity of cloud travel, km/hour: 4
Direction of cloud travel, deg: 323
AI area length, m: 20000
AI area width, m: 20000
Radius of a circular platform, m:

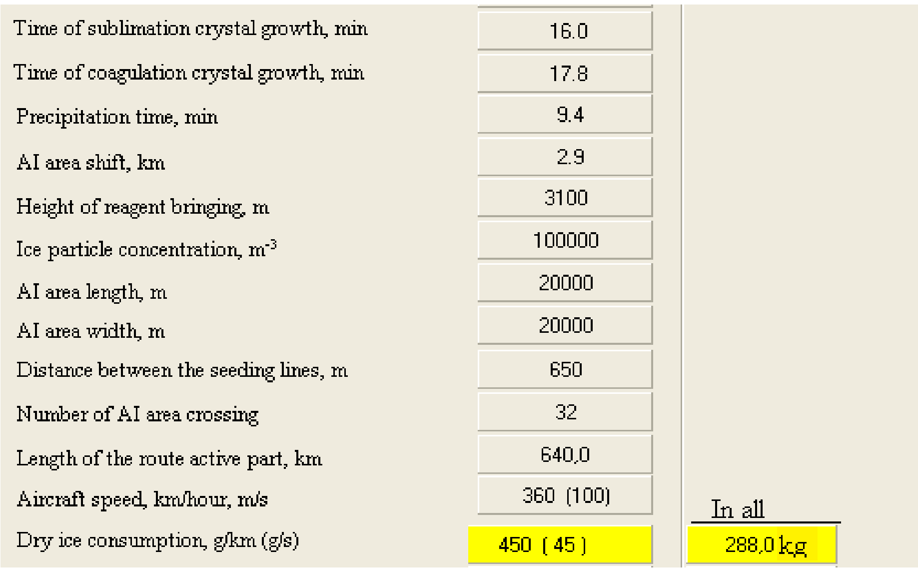
Area type
● Square
○ Round

Type of aircraft
● Airplane

Following are similar results of AI parameters calculation (with allowance made for necessary anticipation at known rate of clouds transport by wind) aimed at formation of transparency region over the checkpoint.
Velocity of cloud travel =18 km/h
Direction of cloud travel = 300 deg
Sublimation crystal growth time = 12.6 min
Coagulation crystal growth time = 35.4 min
Precipitation time = 1.4 min

Shift of AI area = 14.8 km
Height of reagent application =3000 m
Ice particle concentration = 10000/m^3
Distance between seeding lines = 500 m

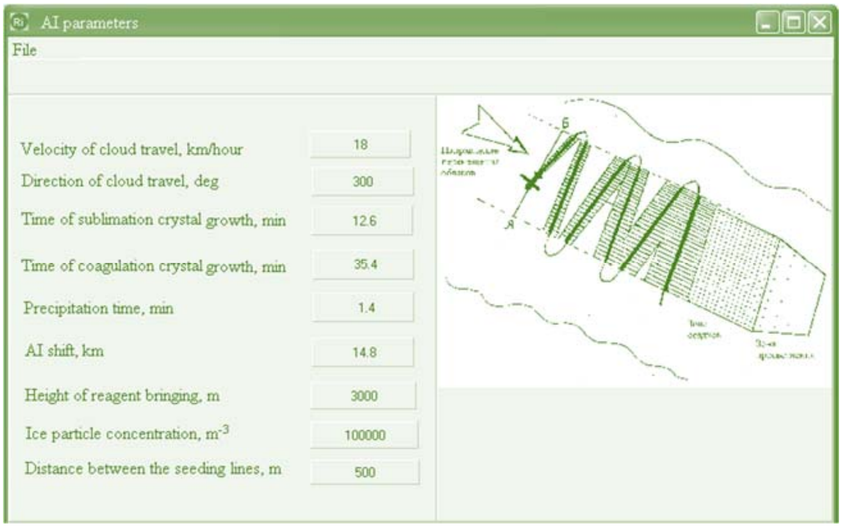
Figure 3. AI characteristics



Time of sublimation crystal growth, min	16.0	
Time of coagulation crystal growth, min	17.8	
Precipitation time, min	9.4	
AI area shift, km	2.9	
Height of reagent bringing, m	3100	
Ice particle concentration, m^{-3}	100000	
AI area length, m	20000	
AI area width, m	20000	
Distance between the seeding lines, m	650	
Number of AI area crossing	32	
Length of the route active part, km	640.0	
Aircraft speed, km/hour, m/s	360 (100)	In all
Dry ice consumption, g/km (g/s)	450 (45)	288.0 kg

The diagram of stratiform clouds seeding with area transfer is presented in Figure 4.

Figure 4. Active window of the AI area parameters



Velocity of cloud travel, km/hour	18
Direction of cloud travel, deg	300
Time of sublimation crystal growth, min	12.6
Time of coagulation crystal growth, min	35.4
Precipitation time, min	1.4
AI shift, km	14.8
Height of reagent bringing, m	3000
Ice particle concentration, m^{-3}	100000
Distance between the seeding lines, m	500

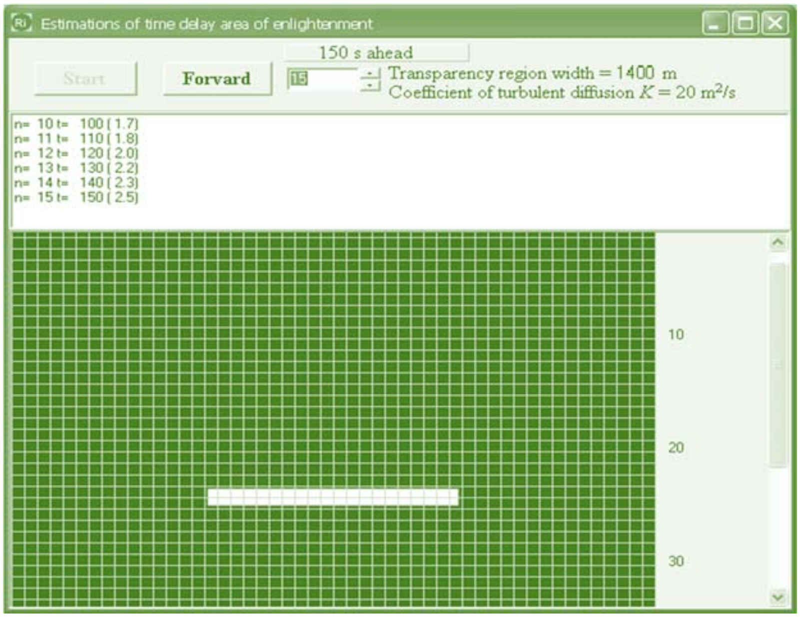
Let us consider the results of modeling transparency regions covering. The initial conditions are as follows: transparency region width = 2000 m; coefficient of turbulent diffusion K = 20 m^2/s. The results of calculations are presented in Table 5.

Table 5. Time characteristics of the width of transparency region

Iteration	Time (s)	Width of transparency region (m)
15	150	1400
30	300	1200
60	600	1100
75	750	1000
105	1050	800

Using the developed model, we calculated covering of rectangular (Figure 5) and round (Figure 6) transparency regions. Area type, coefficient of turbulent diffusion and other parameters are specified in the model. The results of calculations show that the transparency region with diameter of 2000 m can exist for up to 20-30 min at coefficient of turbulent transport K = 20 m^2/s; in this case the area is about 40% the initial one.

Figure 5. Active window of calculating the transparency region covering



150 s ahead

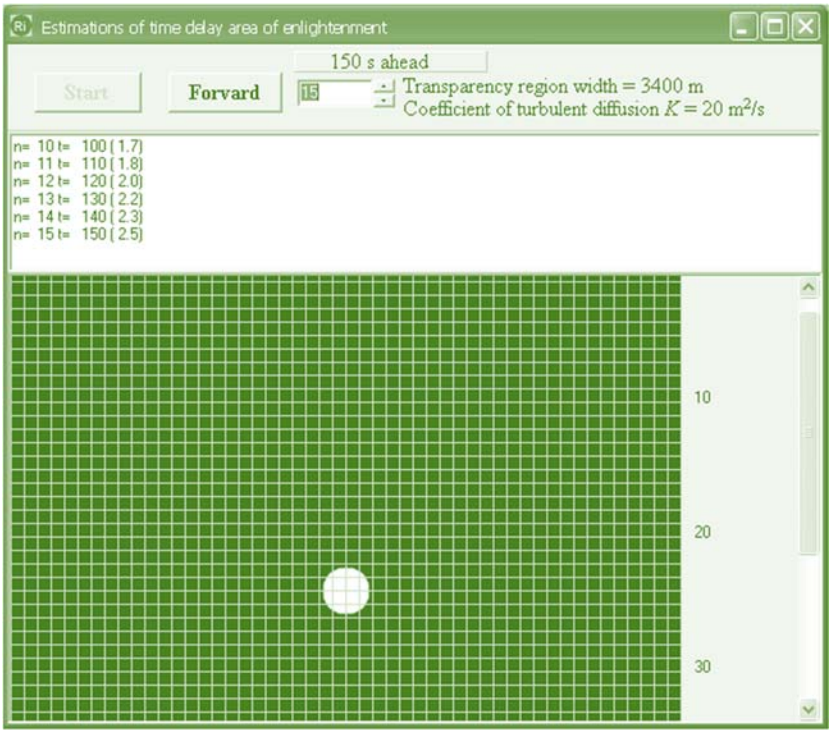
15

Transparency region width = 1400 m

Coefficient of turbulent diffusion K = 20 m^2/s

```
n= 10 t=  100 ( 1.7)
n= 11 t=  110 ( 1.8)
n= 12 t=  120 ( 2.0)
n= 13 t=  130 ( 2.2)
n= 14 t=  140 ( 2.3)
n= 15 t=  150 ( 2.5)
```

Figure 6. Active window of calculating the transparency region covering for a round area



150 s ahead

15

Transparency region width = 3400 m

Coefficient of turbulent diffusion K = 20 m^2/s

```
n= 10 t=  100 ( 1.7)
n= 11 t=  110 ( 1.8)
n= 12 t=  120 ( 2.0)
n= 13 t=  130 ( 2.2)
n= 14 t=  140 ( 2.3)
n= 15 t=  150 ( 2.5)
```

We also calculated growth of man-made crystals in fog. The initial version data were as follows:
Air (fog) temperature T_a = –5 ^{o}C
Air pressure P = 1000 mbar
Fog water content q_1 = 0.3 g/m^3
Average fog drop radius r_{1av} = 5 μm
Concentration of fog drops n_1 = 5.73·10^8 m^{-3}
Visible range before influence L_0 = 43 m

Radius of man-made crystals $r_0 = 2\ \mu m$

The results of modeling are given in Table 6. The meteorological range of visibility (MRV) increases as water vapor is distilled from drops to crystals (drops evaporation). The results of calculations show that visible range in fog increases by 247 m for 8.5 min.

Table 6. Results of calculations on polydisperse fog scattering

Concentration of man-made ice particles (m^{-3})	Time of transparency, t_{tr} (min)	Final crystal size, r (μm)	MRV, L (m)
10^4	90.5	204	1485
$5 \cdot 10^4$	36.6	129	748
$1 \cdot 10^5$	24.4	105	564
$2 \cdot 10^5$	16.1	84	435
$3 \cdot 10^5$	13	75	368
$4 \cdot 10^5$	10.7	68	336
$5 \cdot 10^5$	9.9	64	304
$6 \cdot 10^5$	8.5	60	290
$7 \cdot 10^5$	7.8	57	274
10^6	6.9	51	236

Conclusions

Using the developed model to calculate dissipation of clouds and fogs, we obtained refined data on the rate of transparency areas formation. Our model makes it possible to calculate the rate of fog transparency formation as well as final crystal size and MRV in fog depending on dosage of man-made ice crystals bringing to fog *et al.*

The calculations on influence of man-made crystals on supercooled fog were performed. It was found that the rate of transparency areas formation in supercooled clouds and fogs essentially depends on concentration of bringing man-made crystals; it may vary from several minutes up to several tens of minutes. At crystal concentrations of $3 \cdot 10^5\ m^{-3}$ and more, the time of dissipation is 5–7 min on the average; in this case, MRV increases by 500 m and more. To form 200–300 m transparency regions in fog, one should bring reagent with concentration of $10^6\ m^{-3}$. In this case, the estimating time of transparency approach is 3–5 min, depending on fog water content and dispersion.

Our model may be applied when choosing optimal reagent concentration *et al.* with allowance made for thermodynamic conditions of ambience and microphysical characteristics of clouds and fogs as well as responsiveness of action.

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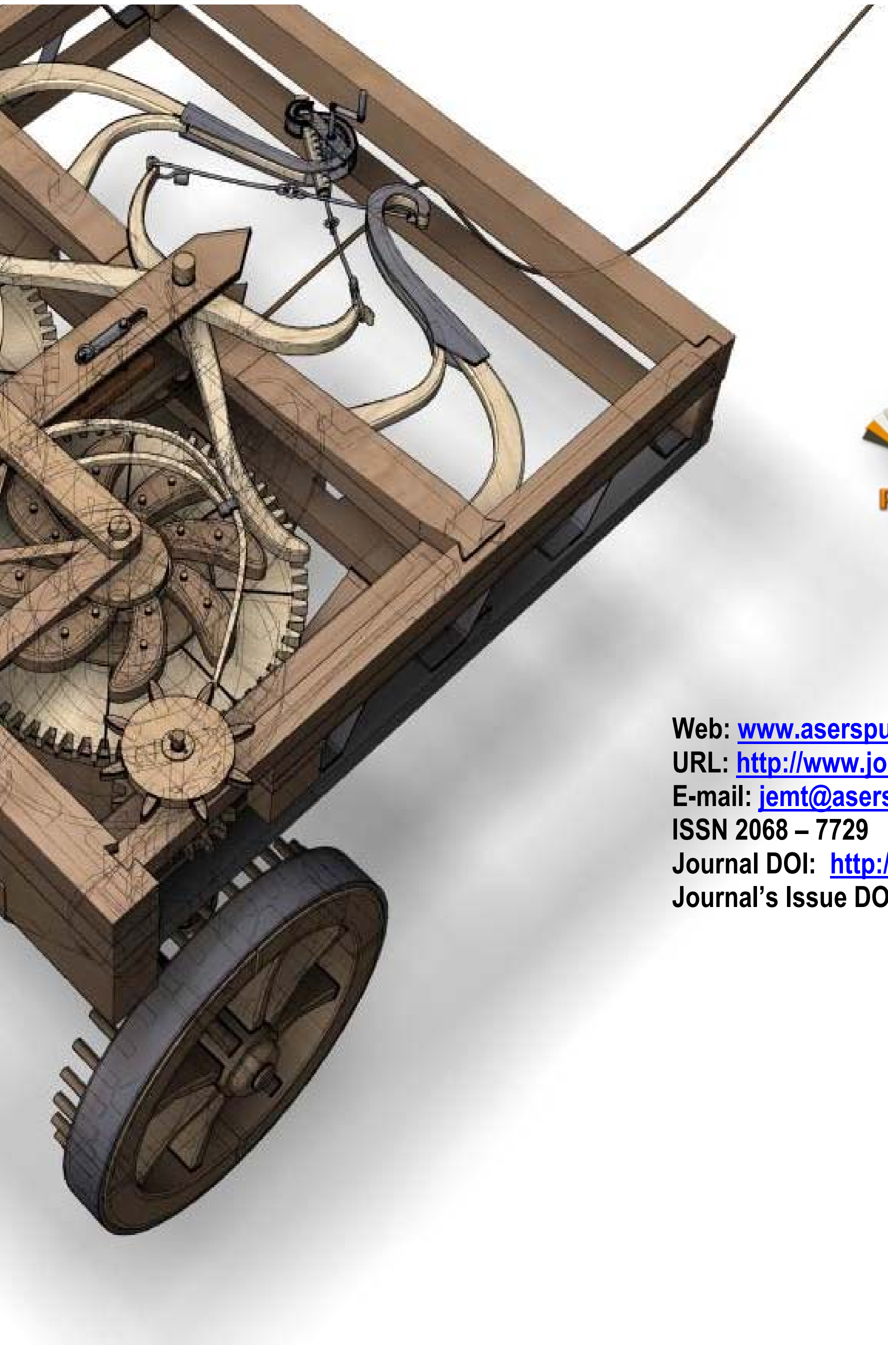

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