Numerical Analysis of Effects of Atmospheric Ice Nuclei Concentrations on Radiant Properties of Cold Clouds

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ABSTRACT

Numerical simulations of 18 precipitation days from June to September in 1996 with the 3D convective cloud model of CAMS (Chinese Academy of Meteorological Sciences, Version 2000) were conducted. In these simulations, the concentration of IN (ice nuclei) was assumed to increase by 5 times. The results show that when IN concentrations increase, the amounts of precipitation decrease, cloud tops heighten and the areas of cloud tops increase in 80 percent simulated clouds. Moreover, in 95 percent simulated clouds, the sizes of ice crystals in clouds decrease and quantities increase. These results mean that the physical properties of clouds will change when IN concentration increases. The radiant properties of clouds and climate may also change directly and indirectly.

Key words: ice nuclei, observation, numerical simulations, climate, radiation

1. Introduction

Researches on the possible effects of CNN (cloud nucleation nuclei) on the radiant properties of clouds and climate have been conducted by many people, but the effects of IN (ice nuclei) have not been analyzed well. In fact, ice nuclei are very important in many weather events. Some observations have showed that IN concentrations increased in some places, so we hope to know the influence of increased IN concentration on cloud properties and climate. For the reason that the synchronous observation of concentrations of IN and ice particles in clouds is difficult, the observation of climate change due to IN concentration change is even more difficult. Statistics shows that clouds cover 67 percent of the global area (Ramanathan et al., 1988). Clouds have both warming effect and cooling effect. Net radiative forcing of clouds is the combination of the two effects. Globally averaged net radiative forcing of clouds is about four times of the warming effect caused by doubled CO₂ concentration (Ramanathan et al., 1988; Harrison et al., 1990). For the reason that clouds are very important to the global radiative process, changes of cloud physical properties may change the global radiative balance to a large extent. The study of cloud radiative forcing is still very difficult now. Nowadays, the atmospheric aerosol concentration increases for human activities and some natural changes. Aerosol can play an important role as CCN or IN in the microphysical process of warm or cold clouds. They can influence cloud precipitation and cloud radiative properties directly and indirectly. Many scientists have conducted researches on climate changes caused by number concentration changes of CCN, such as the studies of Twomey et al. (1984) and Alkezweny et al. (1993). They believe that increase of IN concentrations will restrain warm rain processes, decrease precipitation and increase cloud radiative forcing directly and indirectly. Some studies have verified the existence of the effect. But their
researches are mainly focused on the studies of warm clouds (Francois et al., 2002).

In fact, cold clouds can also be very important to the global radiative balance. Its radiative forcing is one of the most uncertain factors that influence global climate and radiative balance. IN can be very important to cloud radiant properties. When temperature is below $-35^\circ$C, the formation of ice mainly relies on heterogeneous nucleation (Baker, 1997). When the number concentration of IN changes, the microphysical properties of cold clouds will change and the radiative properties of clouds may also change (Ramanathan et al., 2001). Thus, we pay more attention to IN for they may change the radiative properties of cold clouds. There have been some discussions on the influence of IN on cloud physical properties. In 1985, Perez et al. (1985) brought forward the opinion that IN may influence cold clouds. In 1991, Vali (1991) also presented the similar opinion. In the 1960s, You and Shi (1964) conducted researches on ice via observations using an airborne PMS (Particle Measuring System) in Jinlin province in China. They found that ice concentration is higher than the average value and presume that the region is the near-source region of IN. In the 1980s, You et al. (2002) conducted researches on ice clouds using PMS in Hebei province in China. They found that the number concentration of haze was in direct proportion to the concentration of ice crystals in the cloud and in inverse proportion to the size of ice particles.

In the study mentioned above, they presumed that IN concentration may influence physical properties of cold clouds, but they did not study the influence of IN concentration on the precipitation and radiant properties of clouds. Recently, with the increase of number concentration of atmospheric aerosols, IN concentration also increases. In 1963, 1995 and 1996, You and Shi (1964) and You et al. (2002) observed the concentration of IN in the suburb of Beijing using the Bigg mixed cold-cloud-chamber to make these observations be comparable. The Bigg mixed cold-cloud-chamber, which was used in the observation in 1963, was still used in the observations in 1995 and 1996. The mixed cold-cloud-chamber can offer an environment of being very close to IN nucleation in reality. Moreover, the observation method, observation procedure and observation period were the same as in these observations. They found that the concentration of IN in the suburb of Beijing increased greatly. At $-20^\circ$C, it increased by about 15 times. Although there were some influences of pollution and dust, You et al. (2002) believed that the background concentration of IN also increased obviously. Thus, we hope to know the influence of increased IN concentration on cloud properties and climate.

Because the synchronous observation of the number concentration of IN and ice particles in clouds is very difficult in reality, we cannot verify the influence of IN concentrations on properties of ice particles easily. In this paper, a 3D cloud model is used. A number of numerical simulations (18 precipitation events from June to September in 1996) were conducted and the number concentration of IN was assumed to have increased by about 5 or 10 times. (After we consider the observation results of You et al. (2002) and possible pollution influence, we chose the two values.) Then we checked the changes of cloud microphysical and radiant properties. In addition, the possible climate effect is analyzed.

2. Model description

For the reason that climate models have low spatial resolution and do not consider IN-cloud interaction in detail, the CAMS (Chinese Academy of Meteorological Sciences) 3D cloud model is used in the research for it contains very detailed microphysical processes of clouds (Yu and He, 2001; Hu and He, 1987; Zou, 1991). The model considers the supersaturation of vapor and the variation of atmospheric temperature in the ice nucleation process. Thus, the computation results will be much more close to the experimental results in the lab. The model considers five kinds of water materials: cloud water, ice particles, rain water, graupel and hail. The model also considers 29 mutual transformation processes of these particles in detail and can forecast 10 kinds of variables. The model has
60×60 horizontal grids and 30 vertical grids. Its horizontal grid spacing is 0.7 km and the vertical grid is 1.2 km. The parameterized equations of microphysical processes use the results of Hu and He (1988). The dynamics equations use the results of Zou (1991). After several times of modification, it can simulate the physical processes of clouds well.

In the model, the nucleation equation considers the supersaturation of vapor and the variation of atmospheric temperature. The equation is

\[
N_{\text{pvi}} = \begin{cases} 
0 & \text{when } \frac{dT}{dt} < 0 \text{ or } Q_v > Q_{\text{si}}, \\
-N_0B\exp[B(273-T)]/\rho \left( \frac{Q_v - Q_{\text{si}}}{Q_{\text{sw}} - Q_{\text{si}}} \right)^k & \text{when } \frac{dT}{dt} = 0 \text{ or } Q_v = Q_{\text{si}},
\end{cases}
\]

where \(Q_v\) is the specific humidity. \(Q_{\text{sw}}\) and \(Q_{\text{si}}\) are the saturated specific humidity on water surface and the saturated specific humidity on ice surface. \(\rho\) is the density of the atmosphere. \(Q_v-Q_{\text{si}}\) is the supersaturation on ice surface. In the model, the influence of supersaturation is considered. \(N_{\text{pvi}}\) is regarded as in direct proportion to \(\left[ \frac{Q_v - Q_{\text{si}}}{Q_{\text{sw}} - Q_{\text{si}}} \right]^k\). Here \(k\) is 5 in the model.

The number concentration of atmospheric IN is computed by the equation

\[
N_{\text{in}} = N_0\exp[B(273-T)],
\]

where \(N_{\text{pvi}}\) is the concentration of ice particles produced in a certain period by IN. \(N_{\text{in}}\) is the number concentration of IN in the atmosphere. \(N_0\) and \(B\) are two constants given by users. In the model, the experimental results of Fletcher (1962) is used to simulate ice nucleation. That is, \(N_0=6.53, B=0.342\).

3. Numerical simulations using 3D cloud model

3.1 A case study

In this section, a precipitation case was simulated as an example to test the influence of IN concentration changes on the physical properties of clouds. The sounding data of 10 June 1996 in Beijing was used in simulation. On that day, the relative humidity on ground was 33 percent and the height of the zero-degree level was 4 km.

![Fig.1.](image)

**Fig.1.** (a) Radar echo observed at 1437 BT 10 June 1996, (b) simulated radar echo at the 45th minute (Using lengthways section at the 30th grid, the minimum of radar echo is 5 dBz and the space between two lines is 20 dBz).

3.1.1 Comparison of simulated and observed radar echoes

Figure 1a is the radar echo observed at 1437 BT 10 June 1996, and Fig.1b is the simulated radar echo \((N_0=6.53, B=0.342)\) at the 45th minute. In Fig.1a, the maximal height of echo is at about 11-12 km and the maximal intensity is about 60 dBz. In Fig. 1b, the maximal height of the simulated echo is at the 17th-18th grid. The maximal height of the simulated echo is 11.9-12.6 km. The maximal intensity of the simulated echo is about 45-65 dBz. The two figures show that the simulated radar height is very close to observed results and the intensity is also similar. It means that this model has a good ability to simulate actual clouds.
### 3.1.2 Changes of precipitation and physical properties of clouds after IN concentration increased by 5 or 10 times

(1) Precipitation changes

Table 1 shows some simulated changes of cloud physical properties. After IN concentration increased by 5 or 10 times, precipitation is restrained. In addition, cloud top height and updraft velocity increase also. The reason is that the energy released by the nucleation process of a larger number of ice crystals enhances the dynamical structure of clouds. Table 1 shows that the change trend after IN concentration increased by 5 or 10 times is the same.

<table>
<thead>
<tr>
<th>IN concentration</th>
<th>Cloud base height (km)</th>
<th>Maximal cloud top height (km)</th>
<th>Maximal cloud top temperature (°C)</th>
<th>Maximal updraft velocity (m s⁻¹)</th>
<th>Total precipitation rain (kt)</th>
<th>Total precipitation hail (kt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unchanged</td>
<td>1.4</td>
<td>14</td>
<td>-54</td>
<td>39</td>
<td>891</td>
<td>456</td>
</tr>
<tr>
<td>Increased by 5 times</td>
<td>1.4</td>
<td>15</td>
<td>-55</td>
<td>39.5</td>
<td>829</td>
<td>377</td>
</tr>
<tr>
<td>Increased by 10 times</td>
<td>1.4</td>
<td>15</td>
<td>-55</td>
<td>39.5</td>
<td>842</td>
<td>357</td>
</tr>
</tbody>
</table>

**Fig. 2.** IN nucleation velocity (a), content of ice particles (b), and dimension parameters of ice particles (c) in the simulated cloud with normal IN concentration (solid lines), with IN concentration increased by 5 times (lines with crosses), and with IN concentration increased by 10 times (lines with circles).
(2) Changes in physical properties of simulated clouds

After IN concentration increases, IN nucleation velocity increases. The maximal nucleation velocity is about 5 or 9 times after IN concentration increased by 5 or 10 times. Figure 2a shows the IN nucleation velocity in the simulated cloud with the normal IN concentration, with IN concentration increased by 5 times and with IN concentration increased by 10 times. Figure 2b is the concentration of ice particles in three simulated clouds. The ice content increased by 20% and 22% at the 60th minute. Figure 2c is the dimension parameters of ice particles in the three simulated clouds. The reason is that the number of ice crystals increases after IN concentration increases, thus, ice content increased. Moreover, ice particles will be smaller when water content is stable.

These figures show that when IN concentration increases, IN nucleation enhances, ice content increases and ice particle sizes decrease. The variation trends keep unchanged when IN concentration increases by 5 and 10 times. The difference between them is small.

Figure 3 shows the spatial distribution of simulated ice particle concentration at the 57th minute.

3.2 Statistics of 18 precipitation events

From the above simulation we know that when IN concentration increases, some properties of the simulated cloud will change. These changes include ice content increase, ice size decrease and the increase in the length of the lengthways section of the simulated cloud. To confirm the conclusion to be universal, 18 more simulations were conducted. Because the change trends are the same when IN concentration increased by 5 and 10 times, then the simulation with IN concentration just increased by 5 times was chosen.

From June to September in 1996, 26 precipitation events were observed. A series of simulations using the sounding data obtained in these days with normal IN concentration were conducted. All in all, there were 18 precipitation events simulated, which are close to

![Fig. 3](image-url)

**Fig. 3.** Spatial distribution of ice particle concentration in the simulated cloud at the 57th minute (using lengthways section at the 30th grid, the minimum of ice content is 0.1 g kg$^{-1}$ and the space between two lines is 0.2 g kg$^{-1}$): (a) with normal IN concentration, (b) with IN concentration increased by 5 times, and (c) with IN concentration increased by 10 times.
the observation. In these simulations, eight of the simulated precipitation events are a little larger than the observed. It is likely that the maximal precipitation did not pass through the rainfall station, and the rainfall recorder could not measure the largest rainfall. Comparison between simulated and observed rainfall (Fig.4) shows that this model has a good ability to simulate cloud properties, and the simulated results using this model are believable. Figure 4 shows the observed precipitations in the 18 days from June to September in 1996, the simulated precipitation with normal IN concentration, and with IN concentration increased by 5 times. Precipitations decreased by 73 percent in the simulated cloud after IN concentration increased by 5 times. The other simulated rainfall did not change or increased slightly.

Figure 5 shows the proportions of the maximal ice contents $Q_i$ before and after IN concentration increased by 5 times in the simulated cloud. It also shows the proportions of dimension parameters $x_i$.

**Fig.4.** Observed precipitations in 18 days from June to September in 1996 and simulated precipitations with normal IN concentration and with IN concentration increased by 5 times.

**Fig.5.** Ratio of the maximal ice contents ($Q_i$) before and after IN concentration increased by 5 times in the simulated cloud and ratio of the maximal dimension parameters ($x_i$) before and after IN concentration increased by 5 times in the simulated cloud.
before and after IN concentration increased by 5 times in the simulated cloud. Figure 5 shows that in 90 percent clouds, ice content increases and ice particles are smaller after IN concentration increased. It is because more IN in the cloud increase the number of ice particles. Moreover, ice particles are smaller when water content is stable.

In the simulations, when IN concentration increased, the energy released by the nucleation of IN increased. The model can stimulate the development of cloud to a larger extent. The energy can increase updraft velocity, heighten cloud tops, decrease ice particle sizes and increase number concentration. These changes broadened cloud tops. Figure 6 is the proportion of the cloud top areas after the IN concentration increased in the model. In most simulations, the areas of cloud tops were larger. In some simulations, the area of the cloud tops was even doubled. Figure 7

![Fig.6. Ratio of the maximal cloud top areas in simulated cloud after IN concentration increased by 5 times.](image1)

![Fig.7. Maximal cloud top heights in the simulated cloud before and after IN concentration increased by 5 times.](image2)
is the cloud maximum heights before and after IN concentration increased by 5 times. In about 83 percent of the simulated clouds, cloud heights heightened, and the increment was about 0.5-1.0 km. In about 17 percent clouds, there were no macroscopic variation in the bases of clouds, but microscopical variation.

4. Discussion and conclusion: possible changes of radiative properties caused by changes of cloud physical properties when IN concentration increases

The radiant properties of clouds rely on cloud amount, cloud shape, cloud height and other microphysical properties (include phase, shape and number concentration of cloud particles, etc), when radiant flux, latitude and season are the same. From the above mentioned 18 simulations, we can see that precipitation reduces, cloud tops heighten and cloud top area expand in 80 percent simulated clouds after IN concentration increases. In addition, ice content increases and ice sizes decrease in 95 percent simulated clouds. Simulations with the 3D cloud model show that when IN concentration increases, macroscopic and microscopic physical processes will change. Thus, radiative forcing may also change.

Kinne and Liou (1989) analyzed Cs (cirrostratus), which has small particles, and Ci (cirrus), which has big particles. They believed that ice clouds consisting of smaller particles have larger cross-sections and reflectance compared with ice clouds that are constructed by larger particles when their optical depths are the same. Our simulations show that the sizes of ice crystals in the simulated cloud decrease when IN concentration increases. Thus, the reflectance of the simulated cloud will increase. In addition, Roewe and Liou (1978) analyzed the distribution of ice content and computed the warming and cooling rate in cirrus. They believed that thick ice clouds generally have cooling effect. The simulated cloud in this study shows that the tops of thick clouds extend, hence the reflectance of the simulated cloud increases.

Cloud tops influence the shortwave radiative forcing of clouds. Cloud reflectance increases when the cloud is higher. Simulations in this study show that the cloud tops increased for about 0.5-1.0 km in 83 percent simulated clouds. The SBDART radiative model was used to simulate the changes of radiation caused by the changes of cloud heights (Paul et al., 1998). SBDART (Santa Barbara DISORT Atmospheric Radiative Transfer, Version 2.3) is a software tool that computes the plane-parallel radiative transfer in clear and cloudy conditions within the earth’s atmosphere and at the surface. All important processes that affect the ultraviolet, visible, and infrared radiation fields are included. The code is a combination of a sophisticated discrete ordinate radiative transfer module, low-resolution atmospheric transmission models, and Mie scattering results for light scattering by water droplets and ice crystals. The code is well suited for a wide variety of atmospheric radiative energy balance and remote sensing studies. In the simulation, the atmospheric profile used the mid-latitude summer profile and assumed the sun to be located at the zenith. Figure 8 shows the effect of cloud height changes on radiative properties by using the SBDART model. Cloud reflectance increased for about 0.03% to 0.17% in 83 percent clouds at 0.55 μm. We obtained the same result at other wavelength (figures omitted). That is, cloud reflectance increased when cloud tops heightened. Thus, the cooling effect of clouds was enhanced.

Decreased precipitation will result in indirect radiative forcing. The obvious effect of precipitation on aerosols will be weakened after precipitation decreases. The collision among particles is restrained when ice particles are smaller. Thus, clouds can exist for a longer time and cloud amount increases. Thus, the radiative forcing of clouds may be enhanced.

Simulations show that the macroscopical and microscopical physical properties of cloud changed in 80 percent simulated clouds when the number concentration of IN increased. Thus, the reflectance of clouds increased directly and indirectly when IN
concentration increased. This may bring about climate effect. In addition, the 3D convective cloud model was used in the research, so the results may have some limitation. For the reason that stratiform clouds have similar microphysical processes to convective clouds and their updraft velocity is smaller, we assume that when IN concentration increases, the microphysical properties of stratiform clouds will also change but macroscopical properties may not change obviously. That is, the radiative properties of stratiform clouds may also change. It will be further studied. To complete the work, we need to make observation of microphysical and radiative properties of ice clouds by means of planes, satellites, etc. Furthermore, we should research the radiative properties of ice clouds constructed by non-spherical particles theoretically. By this way, we can have a better knowledge of the influence caused by increased IN concentration.

REFERENCES


