Observation of the Degree of Glaciation in Middle-Level Stratiform Clouds

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Abstract

Middle-level stratiform clouds associated with cyclones were observed in spring 1985 simultaneously by a 19.35 GHz microwave radiometer and an 8.6 mm-radar. The vertically integrated liquid-water content was estimated by analysing the data of the microwave radiometer together with upper-air sounding data, and the vertically integrated ice content was estimated from radar-echo intensity. Structure and precipitation formation in middle-level stratiform clouds were studied, especially their degree of glaciation which is defined by the ratio of vertically integrated ice content to the total amount of condensed water (the sum of vertically integrated liquid-water and ice).

Analysed cases are divided into two types of clouds (type-A and type-B). Type-A clouds showed a low degree of glaciation, a large amount of integrated liquid-water, and a comparatively thin and weak radar-echo layer only at middle levels. The degree of glaciation in three cases was slightly less than 10% and an average and the total amount of condensed water was about 55 mg/cm². Type-B clouds had a deep and intensive radar-echo layer, whose tops were far above middle levels. The degree of glaciation in three cases was about 65% on average and the total amount of condensed water was about 40 mg/cm². The degree of glaciation was significantly different between the two types, though total condensed-water amounts were comparable.

The structure and precipitation formation processes of the two types of clouds can be summarized as follows. The type-A cloud is a one-layer middle-level cloud. Ice particles are initiated near its top where the air temperature is not low enough to allow a sufficient number of ice-nuclei to be activated. The glaciation process is not efficient though the supercooled water content is large due to strong updraft in it. On the other hand, the type-B cloud is composed of an upper-level cloud and a middle-level cloud which seem to have formed independently. Ice particles supplied by the upper-level cloud promote the glaciation in the middle-level cloud. By comparing glaciation processes in two types of clouds we showed quantitatively that only a middle-level stratiform cloud could not produce solid precipitation efficiently, even though it contains a large amount of super-cooled water, unless an upper-level cloud supplies sufficient ice particles to it.

1. Introduction

Interesting findings on the precipitation of middle-level stratiform clouds in recent years are a banded mesoscale structure of rainfall and a “seeder-feeder” process. Hobbs et al. (1980) showed that precipitation is initiated in high-level clouds (“seeder” clouds) and it is enhanced in deep stratiform clouds (“feeder” clouds) which exist below seeder clouds and above the 0°C level. It is found in warm-frontal rainbands that there are two types of feeder clouds. In one type of the feeder cloud vertical air motion is weak and rather uniform horizontally (Herzegh and Hobbs, 1980; Matejka et al., 1980). Precipitating particles grow mainly by deposition in it. In the other type of the cloud more intensive updraft causes the feeder cloud and allows precipitating particles to grow by riming as well as deposition in it. (Houze et al., 1981; Rutledge and Hobbs, 1982). However, it remains an unsolved but
rather interesting problem as to what degree of glaciation is attained in feeder clouds and how a different degree of glaciation is dependent on cloud-type. Glaciation degree, which is defined by the ratio of ice content to the sum of liquid-water content and ice content, is very important in understanding the formation process of precipitation in middle-level stratiform clouds.

Though the estimation of supercooled cloud water content in middle-level stratiform clouds is indispensable for solving this problem. There have been few observations of cloud-water amount except from aircraft in a small part of a cloud. Remote sensing is expected to provide one possibility of estimating cloud-water amount. Takeda and Horiguchi (1986) attempted to detect supercooled water droplets in stratiform clouds by measuring the depolarization ratio of a laser signal backscattered from particles in a cloud. A microwave radiometer would also be a good instrument for measuring liquid water in clouds. This idea presented in 1960s has been discussed by several authors (for example, Wilheit, 1972; Staeline et al., 1976; Wilheit and Chang, 1980). Takeda and Natsuki (1982) and Takeda and Liu (1987) discussed the influence of difference in the size-distribution of large water drops. They state that the influence is hardly significant when water drops are smaller than about 300 μm in radius.

The aims of the present study are (1) to estimate the degree of glaciation of middle-level stratiform clouds by remote-sensing observations and (2) to discuss the structure and precipitation formation of middle-level stratiform clouds on the basis of their degree of glaciation. Observations were made of clouds associated with subtropical cyclones around Japan. A microwave radiometer of the National Institute of Polar Research was used to estimate the vertically integrated amount of liquid-water in clouds. Simultaneously, measurements were made using a vertically pointing 8.6 mm-radar of Nagoya University, which allows us to estimate the amount of solid precipitating particles.

2. Data

A 19.35 GHz radiometer and a vertically-pointing radar of 8.6 mm in wavelength were used to estimate liquid-water and ice-water amounts. Radar observations were made only before the initiation of rainfall. Since the formation of large water drops is not expected in middle-level stratiform clouds above the freezing level, it is concluded, in consideration of the detectable limit of our radar, that radar echoes above the freezing level resulted mainly from large ice particles. For this reason we estimated the ice content in a cloud from its radar-echo intensity.

In the atmosphere, most radiation at a frequency of 19.35 GHz results from water droplets in a cloud, water vapor and oxygen. The emission from ice particles in a cloud is negligible at this frequency. Upper-air sounding data at Hamamatsu Meteorological Station were used to estimate the emission of water vapor and oxygen. Estimation errors will be discussed in section 6. The observation of microwave radiation was confined to before the initiation of rainfall, because rainwater deposits on the antenna of the radiometer would result in grossly incorrect data.

In estimating the vertically integrated liquid-water content, we divide the atmosphere into 3 layers and locate a cloud in the middle layer, as shown in Fig. 1. The averaged temperature, emissivity and transmittance of atmospheric gases in each layer are expressed by $T_i$, $e_i$ and $t_i$.

![Fig. 1. Model of the assumed atmosphere. A cloud is in the middle layer.](image-url)
(i=1, 2, 3). The emissivity and transmittance of the cloud are $\varepsilon_i$ and $t_i$. Then,

$$
\begin{align*}
\varepsilon_i + t_i &= 1, \quad (i=1, 2, 3) \\
\varepsilon_c + t_c &= 1.
\end{align*}
$$

(1a) (1b)

And the whole emissivity ($\varepsilon$) and transmittance ($t$) of the layer 2 are given by:

$$
\varepsilon + t = 1,
$$

(2a)

and

$$
l = t_c t_2.
$$

(2b)

Brightness temperature ($T_B$) measured by the microwave radiometer can be written:

$$
T_B = \varepsilon_3 T_3 + \varepsilon_2 T_2 t_1 + \varepsilon_1 T_1 t_1 t_2 + T_{BO} t_1 t_2 t_3,
$$

(3)

where $T_{BO}$ is 3 K cosmic radiation.

Using eqs. (1a) to (3), the following relation can be attained:

$$
\varepsilon_c = \frac{T_B - T_{Ba}}{t_2 t_3 (T_3 - \varepsilon_3 T_1 - T_{BO} t_1)},
$$

(4)

where

$$
T_{Ba} = \varepsilon_3 T_3 + \varepsilon_2 T_2 t_1 + \varepsilon_1 T_1 t_1 t_2 + T_{BO} t_1 t_2 t_3.
$$

(4a)

is the brightness temperature in the case of no cloud.

Since $T_3$ is much greater than $(\varepsilon_3 T_1 + T_{BO} t_1)$ and $t_1$ approximately equals 1 at 19.35 GHz, eq.(4) can be simplified:

$$
\varepsilon_c = \frac{T_a (T_B - T_{Ba})}{T_3 (T_a - T_{Ba})},
$$

(5)

where

$$
T_a = \frac{T_{Ba}}{1 - t_1 t_2 t_3}
$$

(5a)

is the average temperature of the whole atmospheric layer, which can be evaluated by averaging air temperature vertically, weighting with the absorption coefficient. In eq.(4) $T_{Ba}$ is calculated allowing for the absorption of oxygen and water vapor by using upper-air sounding data (Barrett and Chung, 1962; Meeks and Lilley, 1963).

On the other hand, the brightness temperature emitted by a cloud ($T_{BC}$) is given by the next integration:

$$
T_{BC} = \int_0^\infty T_e(x) \exp(-x) dx,
$$

(6)

where $T_e$ is the cloud temperature and $\tau$ is the cloud optical depth in the radiometer-beam direction. Substituting the mean temperature of layer 2 ($T_2$) for the cloud temperature ($T_e$), eq.(6) becomes:

$$
T_{BC} = T_2 \int_0^\infty \exp(-x) dx = T_2 [1 - \exp(-\tau)].
$$

(6a)

From the definition of $\varepsilon_c$, we find also:

$$
\varepsilon_c = T_{BC}/T_2 = 1 - \exp(-\tau).
$$

(6b)

Let $a_e$ and $H_e$ represent the average absorption coefficient of cloud droplets and cloud depth, respectively. Then $\tau$ can be written:

$$
\tau = a_e H_e.
$$

(6c)

On the assumption that water droplets in a cloud are small, $a_e$ is expressed by (Gunn and East, 1954):

$$
a_e = \frac{6\pi}{\lambda} \frac{M_l}{\rho} \text{Im}(-K),
$$

(7)

where $M_l$ and $\rho$ are liquid water content and density of water, respectively. $\lambda$ is the wavelength of the radiometer and $K$ is a coefficient related to the complex refractive index of water droplets. $\text{Im}(-K)$ represents taking the imaginary part of $(-K)$.

Combining eqs.(6b), (6c) and (7), $\varepsilon_c$ can be related to integrated liquid-water amount (L) by:

$$
\varepsilon_c = 1 - \exp(-AL),
$$

(8)

where

$$
A = \frac{6\pi}{\lambda \rho} \text{Im}(-K).
$$

(8a)

The vertically integrated liquid-water content in a cloud can be evaluated on the basis of the brightness temperature ($T_B$) observed by the microwave radiometer, by using eqs.(5) and (8). The assumption of small water droplets is reasonable in the present study.
3. Two different types of observed stratiform clouds

Observations were made from April to June in 1985 at Nagoya. We analysed the cases in which layer radar echoes existed at middle-levels in association with travelling cyclones. On the basis of the vertically integrated liquid-water content and the radar-echo intensity, we found two different types of stratiform clouds among analysed cases. A type-A cloud showed a comparatively thin and weak radar-echo layer only at middle levels, but a large integrated liquid-water content. A type-B cloud has a deep and intensive radar-echo layer whose top is far above middle levels, but has a small integrated liquid-water amount. In other words, type-A clouds are at middle levels and predominantly abundant in liquid water. Type-B clouds are composed of both middle-level clouds and upper-level clouds, and ice (large ice particles) is predominant in them.

Of course, other types of clouds were also observed, such as a cloud in which both liquid-water and ice-water amounts were small. We chose type-A and type-B clouds as interesting for the following reasons. (1) They showed a comparatively large amount of total condensed water (the sum of vertically integrated liquid-water and ice). Both of them have a high probability of producing a considerable amount of precipitation. (2) They are significantly different in characteristic features, which implies a different precipitation formation process.

Several parameters of these two types of clouds are summarized in Table 1. The vertically integrated radar-echo intensity (R) reflects the vertically integrated amount of ice particles in a cloud, though R and integrated ice content are not in a proportional relationship. It can be seen that the integrated liquid-water amount in a type-A cloud is larger, but the integrated ice-water amount is smaller than in a type-B cloud. Moreover, type-B clouds indicate a higher echo-top and a lower air temperature at the top than type-A clouds. In the typical clouds of type-A (5 May) and type-B (26 April), the echo-top was 5.0 km and 9.5 km and air temperature at the top was $-6^\circ$C and $-35^\circ$C, respectively.

4. Detailed description of each case

1) Case of 6 to 7 April

On 6 to 7 April low pressure moved northwestward from the East China Sea (Fig. 2) and on the late 7th its center passed near Nagoya. Clouds associated with the low pressure system covered a much broad area in front of its center.

The time-height cross section of radar-echo intensity from 17:10 on 6 to 9:00 on 7 April in 1985 is shown in the upper part of Fig. 3. There were two periods of relatively intense radar echo before the initiation of rainfall – period I: 17:10

<table>
<thead>
<tr>
<th>Case</th>
<th>Date</th>
<th>Time</th>
<th>L</th>
<th>R</th>
<th>$H_f$</th>
<th>$H_{top}$</th>
<th>$T_{top}$</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7 Apr.</td>
<td>6:00-8:00</td>
<td>37</td>
<td>4.8</td>
<td>2.5</td>
<td>6.0</td>
<td>-15</td>
<td>A</td>
</tr>
<tr>
<td>2</td>
<td>5 May</td>
<td>13:25-14:05</td>
<td>71</td>
<td>-7.2</td>
<td>4.0</td>
<td>5.0</td>
<td>-6</td>
<td>A</td>
</tr>
<tr>
<td>3</td>
<td>10 May</td>
<td>12:00-16:00</td>
<td>52</td>
<td>5.2</td>
<td>3.5</td>
<td>7.5</td>
<td>-23</td>
<td>A</td>
</tr>
<tr>
<td>4</td>
<td>6 Apr.</td>
<td>18:00-19:00</td>
<td>5</td>
<td>17.8</td>
<td>2.5</td>
<td>8.0</td>
<td>-30</td>
<td>B</td>
</tr>
<tr>
<td>5</td>
<td>26 Apr.</td>
<td>19:00-20:00</td>
<td>23</td>
<td>17.1</td>
<td>3.5</td>
<td>9.5</td>
<td>-35</td>
<td>B</td>
</tr>
<tr>
<td>6</td>
<td>7 Jun.</td>
<td>21:00-23:00</td>
<td>16</td>
<td>14.5</td>
<td>4.0</td>
<td>9.5</td>
<td>-28</td>
<td>B</td>
</tr>
</tbody>
</table>

L: Vertically-integrated liquid-water amount (mg/cm$^2$)
R: Vertically-integrated radar echo intensity.

\[ R = 10 \log \sum_{i=1}^{n} (Z_i), \quad n=120 \] is sampling-point number in the vertical direction.

$H_f$ : Height of freezing level (km).
$H_{top}$ : Height of echo top (km).
$T_{top}$ : Air temperature at $H_{top}$ ($^\circ$C).
to 20:30 on April 6 and period II: 5:00 to 8:00 on 7 April. The radar echo is delineated sharply at the level of 2 to 3 km during most of the observational period. The height of the freezing level was about 2.5 km. The radar-echo pattern in period I is evidently different from that in period II. In period I, the height of the echo top defined by $-6 \text{ dBZ}$ is about 8 km, where the air temperature is about $-30^\circ\text{C}$, and the radar echo is intense, especially from 18:00 to 19:00. On the other hand, the radar echo in period II has a lower top and weaker intensity, exhibiting a cellular pattern more clearly. Its top is at the level of about 6 km where the air temperature is about $-15^\circ\text{C}$.

The lower part of Fig. 3 shows the time variations of the vertically integrated liquid-water content (L) and the vertically integrated radar-echo intensity (R). The structure of the stratiform clouds observed in this study did not change drastically with time and the time section of the observed data reflects the spatial variation of the clouds passing over the observational site rather than the same cloud in different stages of development. In consideration of the speed of movement of the disturbance and of high altitude winds, a variation of one hour in a time section corresponds approximately to a horizontal range of 50 km. In this paper, we will call a scale of 20 to 200 km (or about 20 minutes to 4 hours in time scale) “mesoscale”.

The integrated liquid-water amount is very low (less than 20 mg/cm$^2$) during period I (17:10 to 20:30). Roughly speaking, the integrated liquid-water amount changes inversely with R until 22:00. At 18:00 to 19:00 the radar echo is at its most intense, but the integrated liquid-water amount falls close to 0 mg/cm$^2$, implying that clouds were well glaciated. After 6:00 on the 7th the integrated liquid-water content is large (sometimes higher than 40 mg/cm$^2$). Interestingly, most peak values of integrated liquid-water content appear to correspond to cells which are seen at intervals of about 30 minutes (about 25 km) in the time-height cross section of radar-echo intensity after 2:30. The corresponding echo-cells and liquid-water peaks are labelled with the same numbers in the upper and lower figures. This correspondence indicates that the number of water drops and the ice particles was large in the same position in the cloud.

The cloud observed from 6:00 to 8:00 is an example of a type-A cloud, which has a large amount of liquid-water but a small amount of ice. The cloud observed from 18:00 to 19:00 is an example of a type-B cloud, which has a large amount of ice, but very little liquid-water.

In estimating approximately the total condensed-water amount in both cloud types, we used a following empirical formula:

$$M = 38Z_e^{1.2}, \quad (\text{mg/m}^3) \quad (9)$$

where $M$ is the ice content. The formula was established by the in-situ measurement of falling snow particles and the radar-echo intensity at 165 m altitude (in 1979, at Canada, Arctics). Fig. 4 shows the results of measurements and the curve of eq.(9). Each point in the figure is attained by a value of $M$ and an average of $Z_e$ over a period of 10 minutes. These data were collected from several precipitation events in which a wide range of air temperatures and many types of snowflakes were involved. Therefore, the relationship between $M$ and $Z_e$ for the clouds of this study may not be much different from eq.(9) even though obtained from a different climatological zone.

It is estimated that the vertically integrated ice content during the period 18:00 to 19:00 on
the 6th is 31 mg/cm² and that during the period 6:00 to 8:00 on the 7th is 4 mg/cm². This estimation means that about 90% of condensed water was glaciated in the former period and only about 10% in the latter period, though their total condensed-water amounts are comparable.

The result of the upper-air sounding at 21:00 on 6 April at Hamamatsu Meteorological Station is shown in Fig. 5. The atmosphere is potentially stable except at levels near the ground. A temperature inversion layer was located around 600 mb level (4.3 km). $\theta_e$ is very different below and above the inversion layer and the relative humidity is very high around the layer. These profiles show the existence of middle-level clouds formed by large-scale lifting near a warm frontal surface.

Figure 6 shows the atmospheric state at 9:00 on 7 April at Hamamatsu Station. Similarly, at 21:00 on the 6th the atmosphere is potentially stable except in a shallow layer near the ground. A warm frontal surface is near the 650 mb level (3.6 km) where the relative humidity is very high.

The atmospheric states shown in Figs. 5 and 6 are similar, characterized by a frontal surface near the 4 km level and potentially stable stratification. But some differences can be still found. The atmosphere above the 400 mb level (7.4 km) is more humid at 21:00 on the 6th than at 9:00 on the 7th. The top of the humid layer where the relative humidity exceeds 60% extends to the level of about 310 mb (9.0 km) at 21:00 on the 6th, while it reaches only the 400 mb level (7.4 km) at 9:00 on the 7th. The comparatively humid layer at upper levels at 21:00 on the 6th is consistent with the existence of upper-level radar echoes. In addition, the layer of 400 to 550 mb seems to be less stable at 9:00 on the 7th than at 21:00 on the 6th (the difference of $\theta_e$ between the two levels is 4.5 K

Fig. 4. Relationship of $M$ (mg/m³) and $Z_e$ (mm⁶/m³).

Fig. 5. Vertical profiles of air temperature (left), equivalent potential temperature (middle) and relative humidity (right) at 21:00 on 6 April, 1985 at Hamamatsu Meteorological Station.

Fig. 6. Same as Fig. 5 except for 9:00 on 7 April, 1985.
at 21:00 on the 6th and 2.5 K at 9:00 on the 7th). The comparatively less stable layer near the upper part of middle-level clouds might have resulted in the more cellular structure of radar echo after 6:00 on the 7th.

2) **Case on 26 April**

On this case Nagoya was in the warm sector of a cyclone, the center of which was in the Sea of Japan, and close to its cold front temporarily. The radar echo from 11:50 to 22:05 on 26 April is shown in Fig. 7. Middle-level echoes were observed persistently. Around 12:00 and 20:00 the echo top reaches about 9.5 km where the air temperature is about -35°C. After 18:00 radar echoes became very intense. Rainfall reached the ground from 18:00 to 19:00 and around 20:40. In addition, streaks were recognized above the 6 km level after 18:00, implying that upper-level clouds contained convective cells.

Liquid-water content was measured from 11:50 to 21:20, except for 17:50 to 18:50 and 20:30 to 20:50 when rainfall reached the ground. The integrated liquid-water content is also shown in Fig. 7 and is small during the whole period. Its value is nearly zero at 12:30 and increases slowly after that time. There is no clear positive correlation between the integrated liquid-water content and the integrated radar-echo intensity. Clouds in this case belong to type-B in our classification; especially note type-B from 19:00 to 20:00. During the period from 14:30 to 17:30 the echo top was lower and the upper-level echo disappeared, but the integrated liquid-water content was not so small.

Integrated liquid-water and ice-water amounts in the period from 19:00 to 20:00 are 23 mg/cm² and 27 mg/cm², respectively. Accordingly, the degree of glaciation is 54%. More than half of the total condensed water was converted into precipitating water in the clouds. It is possible that there were some large water drops in the clouds during this period since the echo layer was thick. The existence of large water drops might result in an overestimation of the integrated liquid-water amount, and the real integrated liquid-water content is possibly smaller than 23 mg/cm². The degree of glaciation...
would have been larger than 54%.

The atmosphere was potentially stable except in the layer near the ground (Fig. 8). The frontal surface aloft is near 600 mb level (4.3 km) where there is a strong temperature inversion layer. The relative humidity exceeds 80% between the 490 mb and the 600 mb level. Middle-level clouds would have formed near this altitude due to large-scale lifting. The atmosphere is comparatively humid at high levels and the layer in which relative humidity exceeds 60% extends to about the 310 mb level. Near the level of the highest echo top (300 mb), the atmosphere is neutral. Upper-level convective cells, the existence of which can be inferred from streaks in radar echoes, might have resulted in this neutral stratification.

3) Case on 5 May

Clouds in this case were in the warm sector of a depression whose center was in the Sea of Japan and moved northeastward. Simultaneous observation by the microwave radiometer and the radar was possible from about 12:00 to 15:40, before rainfall reached the ground. The time-height cross section of the radar echo
intensity is shown in Fig. 9. Radar echoes were weak and their tops were lower than the 5 km level where air temperature was about -6°C.

As seen in Fig. 9, the vertically integrated liquid-water content is very high and its value (averaged for about 3 hours) exceeds 65 mg/cm². However, the integrated ice content is very small. Clouds are typically type-A in our classification. Similarly to that in the case on 7 April, the liquid-water content increased on a time scale of several tens of minutes in accordance with the intensification of the radar echo (12:15 to 12:45, 13:10 to 14:10, 14:30 to 15:00, and after 15:00, corresponding to 20 to 50 km in spatial scale). The corresponding echo-cells and liquid-water peaks are labelled with the same numbers in the upper and lower figures.

The integrated ice content estimated by eq.(9) was about 2 mg/cm² during the period from 13:25 to 14:05 while the integrated liquid-water content was 71 mg/cm². The degree of glaciation is only 3%, and most of condensed water in the clouds was in the form of cloud droplets.

Figure 10 shows the result of the upper-air sounding. The relative humidity is higher than 80% between the 500 mb and 600 mb levels. The atmosphere is potentially stable except for the layer near the ground and the layer between 500 mb and 600 mb. It is noticeable that the layer, where middle-level clouds existed, was neutral. The cellular pattern of radar echoes and a large liquid-water content were observed in this neutral layer.

4) Case on 10 May

Clouds in this case were associated with a depression whose center moved eastward along the latitude of about 31°N. Nagoya was in its northern part. Fig. 11 shows that radar echo was not so intense and exhibited a mesoscale cellular structure (9:00 to 10:10, 14:00 to 15:40 and 16:00 to 18:00, corresponding to a spatial scale of 50 to 100 km). As seen in the lower part of Fig. 11, the integrated liquid-water content is large and its value averaged for several hours is larger than 50 mg/cm². Interestingly, there is a peak value of integrated liquid-water content in each mesoscale cellular radar echo, though the peak values were not observed at the same time as the appearance of intense echoes. The corresponding echo-cells and liquid-water peaks are labelled with the same numbers in the upper and lower figures. Moreover the echo top reached a high altitude in each cell while the echo layer was shallow between cells. These facts suggest that there were some developed clouds, at regular spatial intervals in the middle levels, which possessed stronger updrafts, more condensed water, higher cloud tops and more ice particles than others in their vicinity. These imply the existence of smaller convective cells in mesoscale cells. Streaks were recognized above the 5.5 km level, especially after 15:00. Mesoscale cellular deep echoes would have resulted from these developed smaller cells.

Clouds in this case, especially in the period of 12:00 to 16:00, are type-A. The integrated liquid-water content is 52 mg/cm² and the integrated ice content is 5 mg/cm². Ice content was low even in mesoscale cells where the echo tops reached high altitudes. The degree of glaciation was less than 10%. The upper-air sounding showed a humid layer at middle levels (not shown here).

5) Case on 7 June

In this case Nagoya was in the northern part of a depression the center of which moved northeastward. As shown in Fig. 12 the radar echo often exceeded the 9 km level and the echo bottom descended gradually with time. Rainfall reached the ground after 23:00.

The integrated liquid-water content (Fig. 12)
Fig. 11. Same as Fig. 3 except for 10 May, 1985.

Fig. 12. Same as Fig. 3 except for 7 June, 1985.
was low, and it was less than 20 mg/cm² even just before rainfall started. Its increase with time suggests that middle-level clouds gradually became denser and denser with time. The upper-level radar echo exhibits regular changes in both intensity and top height on time scale of about 100 minutes. It is to be noted, however, that there was no evident increase in the integrated liquid-water content coincidently with the high echo top. Atmospheric processes which are responsible for the development of the upper-level echo and the formation of ice particles at upper levels would be different from processes which result in the formation of many water droplets at middle levels. In other words we can say that the cloud system was composed of an upper-level cloud and a middle-level cloud. The cloud system observed between 21:00 to 23:00 is classified type-B, because the radar echo is comparatively intense, but the integrated liquid-water content is low. The integrated liquid-water and ice content during the period 21:00 to 23:00 are 16 mg/cm² and 16 mg/cm², respectively. The degree of glaciation is 50%.

The humid layer can be recognized at middle levels from upper-air sounding data (not shown here). Middle-level clouds are believed to have been around the 500 mb level (5.5 km), while upper-level clouds existed above them and extended at least up to the 300 mb level (9.5 km). The atmosphere around the 300 mb level is neutral. After the onset of rainfall at the ground, the other radar of Nagoya University (3.2 cm wavelength) revealed the highest echo top to be 11 km and upper-level convective cells to be characterized by streaks.

5. Conceptual models of two types of clouds

The integrated ice-water content and total condensed water for each case of Table 1 is shown in Fig. 13. The degree of glaciation is significantly different between the two types of clouds. In analysed cases its value is 50% to 90% in type-B clouds and less than 10% in type-A clouds, though total condensed water amounts are comparable. In other words, type-B clouds contained more precipitating-water in comparison with type-A clouds.

![Fig. 13. Relationship between total condensed-water amount (T) and vertically integrated ice content (I) in each case of Table 1. Glaciation of 100%, 50% and 20% are shown by solid lines.](image)

Based on the above-mentioned observational facts, conceptual models of two types of clouds can be summarized as follows.

**Type-A clouds**

A type-A cloud would be a one-layer middle-level cloud (Fig. 14). Ice particles are initiated near its top which is not high. Air temperature at the cloud top is not low enough to make a sufficient number of ice-nuclei active. There is a comparatively small amount of ice particles in the cloud, while the super-cooled liquid-water content is high. This type of cloud possesses some convective features, as suggested by the cellular structure of radar echo and potentially neutral stratification in the middle-level atmosphere. An updraft in the cloud is essentially strong and a large amount of liquid-water is generated. But, since there is only a small amount of ice particles, the super-cooled liquid water remains large without being diminished by the growth of ice particles. Generally speaking, the glaciation process in the type-A clouds is not efficient, being less than 10% in all cases analysed here.

Cellular convective updraft results in a larger liquid-water content as well as a higher cloud top than in its vicinity, which in turn allows more ice particles to be created. As a result, the amounts of water droplets and ice particles are large at nearly same place in the cloud, as shown in all of type-A clouds. The observed positive correlation between the liquid-water content and ice content supports the thesis that the type-A cloud is a one-layer cloud.
**Type-B cloud**

A type-B cloud has a thick cloud layer which extends up to upper levels (Fig. 14). Ice particles are initiated at upper levels where the air temperature is lower than $-30^\circ$C, and these particles grow due to falling through the middle-level cloud. "Seeder-feeder" processes occur in this cloud system.

It is likely that the upper-level cloud and the middle-level cloud form independently through different processes and a deep cloud layer, in which the radar echo extends continuously through the layer from middle levels to upper levels, does not form by an air current ascending through it. If the deep cloud system resulted from such an air current, the vertically integrated liquid-water content should be much larger than is observed in our cases. It seems that the middle-level cloud formed as a result of the large-scale lifting of air near the frontal surface aloft, while the upper-level cloud formed through the other process. This might be the explanation of the observed fact that integrated liquid-water content most of which is generated in the middle-level cloud had no positive correlation with the amount of ice particles created in the upper-level cloud, but both water amounts changed more or less inversely in some type-B clouds.

The atmospheric layer near the top of the radar echo (or in an upper-level cloud) is sometimes potentially neutral and convective generating-cells can be recognized in the layer.

The low air temperature at the top of upper-level clouds allows a large number of ice nuclei to be activated. On the other hand, a deep cloud layer from the top of the upper-level cloud to the bottom of the middle-level cloud causes ice particles to grow large. In consequence the amount of ice particles is large in type-B clouds. Meanwhile, the integrated liquid-water content is small because of the growth of a large amount of ice particles and a weak updraft in the middle-level clouds. An inverse relation which was sometimes observed between liquid-water amount and ice-water amount in type-B clouds seems to be consistent with these glaciation processes. Glaciation in type-B clouds is very efficient and its degree was larger than 50% in all cases.

6. **Concluding remarks**

In the previous sections, two types of middle-level stratiform clouds were analysed on the basis of their degree of glaciation. Type-A clouds showed a lower degree of glaciation, larger amount of integrated liquid-water, and a comparatively thin and weak radar-echo layer only at middle levels. The degree of glaciation was slightly less than 10% and the total amount of condensed water was about 55 mg/cm$^2$ on average for 3 cases. Meanwhile, type-B clouds had a deep and intense radar-echo layer, whose top was far above middle levels. The degree of glaciation was about 65% and the total amount of condensed water was about 40 mg/cm$^2$ on
average for 3 cases. A type-A cloud would be a one-layer middle-level cloud. Ice-particles are initiated near its top which is not high and where the air temperature is not low enough to allow a sufficient number of ice-nuclei to be activated. Therefore, the glaciation process in a type-A cloud is not efficient though the super-cooled cloud-water amount is large. On the other hand, a type-B cloud would be composed of an upper-level cloud and a middle-level cloud which are likely to be formed independently. Ice-particles seeded from the upper-level cloud enhanced the glaciation in the middle-level cloud.

In this paper the total amount of condensed water was evaluated by the sum of integrated liquid-water content and the integrated ice content, which were estimated from data obtained from two different detectors. The estimated degree of glaciation might include errors caused in both estimating procedures. Two problems possibly affect the accuracy of the integrated liquid-water content. One is the assumption of small water droplets in clouds. This would sometimes cause an overestimation of integrated liquid-water content, especially for type-B clouds which have very deep echo layers. Numerical calculation of microwave radiative transfer in the cloudy atmosphere (Takeda and Natsuki, 1982; Takeda and Liu, 1987) shows that the overestimation is significant only when the liquid-water amount is larger than about 100 mg/cm². This problem would not be significant, since the amount of liquid-water was less than 100 mg/cm² in all cases, particularly so in type-B clouds. The other error can be caused by the incorrect estimation of water-vapor radiation due to insufficient upper-air soundings (only data at 9:00 and 21:00 LST are available). By numerically calculating the microwave radiation of the atmosphere \( T_{Ra} \), it is found that the difference of \( T_{Ra} \) between data of two soundings, in the worst case, was about 6 K, which is equivalent to a change of integrated liquid-water content of about 18 mg/cm². If we used a single sounding data to calculate \( T_{Ra} \) in eq.(5), error of about 18 mg/cm² would be caused in the estimated liquid-water content when data of the microwave radiometer are collected far before (or far after) the time of the radiosonde release. In order to minimum this error, we used an interpolated value of water-vapor radiation between two upper-air soundings. However, this error must be present to some degree because the water-vapor amount does not always vary linearly with time. But it would become much smaller than that when a single upper-air sounding was used. We estimated that this error would be less than about 10 mg/cm².

Estimation error in ice content is possibly caused by variations in shapes and size distributions of ice particles, and it is difficult to determine quantitatively. For this reason we cannot give an exact figure for the accuracy of degree of glaciation, and estimate roughly that glaciation is less than 10% for type-A clouds and larger than 50% for type-B clouds. We consider that this difference between the types of clouds is significant, though the accuracy still remains to be determined.

The significant difference in the degree of glaciation between type-A and type-B clouds results mainly from (1) the existence of an upper-level seeding cloud and (2) the intensity of an updraft at middle levels. Upper-level clouds in type-B clouds must have played an important role in promoting the glaciation in middle-level clouds by supplying many more ice particles than in type-A clouds. Meanwhile, total amount of condensed water in the type-B cloud system was less than in the type-A cloud. This fact suggests that the middle-level cloud in the type-A cloud is more developed than in the type-B cloud. In other words, the middle-level updraft is stronger in type-A clouds. The important result of the present study is to have shown quantitatively that a middle-level cloud could not efficiently produce solid precipitation even though it forms by a strong updraft, unless an upper-level cloud supplies a sufficient amount of ice particles to it.

A statistical study on the stratiform precipitation was made on the basis of the observation by a vertically-pointing 3.2 cm wavelength radar in spring and the Baiu season of 1985 and spring 1987 at Nagoya University. It shows that most of non-convective precipitation in spring around Nagoya can be produced by type-A and type-B clouds, though other types of precipitation are
frequently observed during the Baiu season. We will give a more detailed discussion of this study in future. There will be another problem to be solved in future — what atmospheric situation is favourable for the formation of each cloud type?

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References


マイクロ波放射計と8.6mm波レーダーによる中層層状雲の氷晶化度の観測

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1985年春，日本付近を通過する低気圧に伴う層状雲について，19.35 GHzマイクロ波放射計と8.6mm波レーダーによる同時観測を行った。マイクロ波放射データから鉛直積分水蒸気（L）を，また，レーダーデータから鉛直積分氷水蒸気（I）を評価し，雲全体としての氷晶化度 [I/（L + I）] を求めた。

その結果，層状雲には2つのタイプ（タイプAとタイプB）のものがあることがわかった。タイプAの雲は氷晶化度が低い，雲水蒸気が多いが，レーダーエコーが中層だけにあり，氷粒子の量は少ない。3ケースの平均総積水蒸気（L + I）が約55mg/cm²であり，氷晶化度は10％弱である。タイプBの雲はレーダーエコーが強く，中層だけでなく上層でも観測される。氷粒子の量が多いが，雲水蒸気は少ない。3ケースの平均総積氷水蒸気が約40mg/cm²で，氷晶化度は約65％である。つまり，両タイプの雲は総積水蒸気がそれほど違わないにもかかわらず，氷晶化度がかなり異なる。

両タイプの雲の構造と降水形成過程については次のように考えられる。タイプAの雲，中層にある一層の雲であり，氷粒子が中層雲の雲頂上近くで形成される。雲頂での気温が十分低くないため，形成される氷粒子数は数少ない。雲水蒸気が多く，中層での上昇気流がかなり強いと考えられる。氷晶化はあまり進んでいない。一方，タイプBの雲は上層雲と中層雲からなる2層の雲であり，上層雲から中層雲への多くの氷粒子のseeding により中層雲の氷晶化度は非常に高くなっている。本研究は，降水形成過程が異なる2つのタイプの雲の氷晶化度を調べたことによって，中層雲だけではなく降が形成されにくく，上層雲からのseeding が降水の形成に重要な役割をはたしていることを，定量的に示した。