An Experimental Study of the Microstructure of Shallow Orographic Cumuli with Precipitation

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Abstract

The observation of the microphysical structure of shallow orographic cumuli was carried out from its initial stage to the precipitation stage.

Cloud droplets larger than 100 μm in diameter were observed in a relatively short time, whenever the cloudy thermal was developed pulsationally in proto-cloud. The proto-cloud is a kind of cloud that has already appeared before a new cloudy thermal begins to develop. It has a relatively broad spectrum of low concentration. The analysis of the microstructure of cloud suggests that the cloudy thermal gradually reaches higher levels and carries up the larger droplets as well as numerous smaller droplets which were formed in the new rising thermal.

The formation of the proto-cloud and the interaction between the proto-cloud and the new cloudy thermal seems an important mechanism for the formation of precipitation from a shallow orographic cumulus.

1. Introduction

The growth of incipient raindrops by collision and coalescence with smaller droplets was treated in detail by Bowen (1950), Ludlam (1951) and others, and it is well established that the larger cloud droplets of diameters exceeding about 50 μm are required to initiate precipitation by the coalescence mechanism. However, condensation theories show that such larger droplets are not likely to grow by condensation on general hygroscopic nuclei in natural clouds. (Howell, 1949; Mordy, 1959 and Mason and Chien, 1962, and others). Accordingly many workers direct their attention to the mechanism of formation of these larger cloud droplets. Woodcock (1950) suggests that the larger droplets may be supplied as giant salt nuclei in the sub-cloud layer, which are generated as spray droplets of 50 μm in diameter. In maritime cumulus, the appearance of the larger droplets may reasonably be attributed to condensation on giant sea salt nuclei, but, some shallow orographic cumulus often has the larger droplets and acts to release a shower. It will be particularly difficult to explain the source of the larger cloud droplets in the continental cloud by giant salt nuclei. Various attempts have been made to explain the mechanism of production of
the larger droplets without recourse to the giant sea salt nuclei. For example, EAST and MARSHALL (1954) and SAFFMAN and TURNER (1956) investigated the effect of turbulent motion in cloud on the collision among small droplets. TELFORD (1955) notes that the concentration of the larger droplets is very low compared with common cloud droplets and tries to explain the growth of the larger droplets by a stochastic model. The stochastic equation for the growth of cloud droplets by coalescence was treated in various ways by many workers (TWOMEY, 1964, 1966; BERRY, 1967; WARSHAW, 1967, and SCOTT, 1968, and others).

These theories have not yet been proved in the natural cloud, because it is hard to relate the microphysical structure of a precipitating cloud with every stage of the cloud.

We had a chance to trace the evolution of the cloud droplet size spectrum in a shallow orographic cumulus from its initial stage to the precipitation stage. The results of the observation seem to suggest a mechanism of precipitation formation by coalescence in shallow orographic cumulus without appealing to the condensation on giant sea salt nuclei.

2. Observation sites and general description of orographic cumuli in the Nikko district

In order to investigate the production of the larger cloud droplets in shallow orographic cumulus, the microphysical observations of orographic cumuli were carried out

Fig. 1. The geophysical map around the observation sites.
around Chuzenji Lake in Nikko city on 12th of September 1966. The geographical features around the lake are shown in Fig. 1 and the observation sites are shown with black joints. The east side of the lake, 1300 m above sea level, was chosen as the center of observation sites. Chanoki-daira, 1620 m above sea level, and about 1500 m to the southeast of the lakeside, and Akechi-daira, 1200 m above sea level, and about 2000 m to the southeast by east, were chosen as the second site.

The Nikko district abounds with mountain masses and shows a complex geographical structure. In general, orographic cumuli develop sporadically over the sunny slope of each mountain mass in summer. Drifting along the slopes with the general airflow and gradually coalescing, the cumuli grow into stratocumulus. The speed of the general airflow is usually less than about 30 cm/sec in this season. Therefore, the movement of the cloud is usually very gentle. The sky is soon overcast with these clouds and a drizzle begins to fall from some of the clouds. It grows very often into a heavy shower.

3. Observation techniques

In the observations, the size of cloud droplets, air temperature, wind speed and direction were measured at three sites. The size of droplets was measured by MgO technique. A slide covered with MgO upon a silicn oil (Kc-88, Shinetsu Kagaku Co.) coated film surface was placed horizontally in a cloud for a fixed time to collect settling cloud droplets. The method can be used with satisfactory accuracy only for cases when the vertical wind velocity is negligibly small. However, we dared to take this method for the sampling of droplets, because the larger droplets could be collected thus through simple procedures. Stokes' and Gun-Kinzer's formulae for fall velocity of cloud droplets were used to obtain the droplet size spectrum or concentration. The ratio of the trace on MgO film to the true size of droplets was assumed as 0.75. Air temperature was measured by the mercury thermometer, wind velocity and direction by the viram-type air meter. As the air meter was not good enough for measuring light wind less than 20 cm/sec, the wind direction was usually deduced from the moving direction of the cloud.

Furthermore, a transmissometer and a new instrument for measuring larger cloud droplets exceeding 50 μm in diameter were used at the lakeside. The transmissometer measures the decay of illuminated light. The magnitude of the decay was roughly in proportion to the water content of the cloud, but the device was mainly used to decide the time at which the cloud enveloped the site or cleared away from the site. The device for measurement of the larger droplets, which was based on the principle of the rain sensor, was described in the previous paper (SASYô, 1969). The device will be called the larger droplet detector.

4. Results and discussions

The observations were carried out on 12th of September 1966. On that day, the cumuli which were observed developed on the slope face the Ashio district and struck near Akechi-daira. Fair weather cumuli started appearing in the sky from around 0800 J.S.T.. The meteorological station at Nikko, at a distance of about 700 m to the west of the lakeside, reported the cloud form and amount as in Table 1.
The wind velocity was light and less than 20 cm/sec throughout the observational period. The results are shown in Fig. 2 where curve (a) shows the five-minute averaged values of the decay of light measured by the transmissometer, and the averaged value for a minute are also shown by black points. These points show the violent fluctuations of light transmission through the cloud. This is consistent with the violent fluctuations of droplet concentration to be discussed below.

The concentration of cloud droplets in cm$^3$ at the lakeside is illustrated by curve (b) in the figure. It is mostly contributed by cloud droplets less than about 30 $\mu$m in diameter because the concentration of larger cloud droplets was very low in comparison with smaller ones. The curves (c), (d) and (e) show the number of cloud droplets counted by the 50 $\mu$m-, 100 $\mu$m- and 200 $\mu$m-sensors of the larger droplet detector for a minute. These droplets will be called hereafter 50 $\mu$m-, 100 $\mu$m- and 200 $\mu$m-

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Fig. 2. The results: curve a, the decay of light illuminated measured by the transmissometer; curve b, the concentration of cloud droplet at the lakeside; curves c, d and e, the 50 $\mu$m- 100 $\mu$m- and 200 $\mu$m-droplets counted by the larger droplet detector respectively; curves f and g, the concentration of cloud droplets at Chanoki-daira and Akechi-daira respectively.
droplet respectively. The curves (f) and (g) show the droplet concentration at Chanoki-daira and Akechi-daira respectively.

A very light shower was observed for several minutes around 1130 J.S.T., but we were not prepared to make accurate observations of it. So our analysis will be based on data obtained after 1130 J.S.T..

4.1 Droplet concentration

The results suggest that a shower began around 1600 J.S.T.. It developed through three different stages characterized by droplet concentration. In the first stage, 1130–1200 J.S.T., the lakeside and Akechi-daira were enveloped in a rather stationary cloud in which concentration, modal diameter and water content calculated from the size spectrum were, respectively, 33/cm³, 20 μm and 0.17 g/m³ at both sites. The cloud had considerably broader size spectrum while the concentration was rather low. On the other hand, Chanoki-daira was enveloped in a very thin cloud, concentration 12/cm³, modal diameter 12 μm and water content 0.03 g/m³. These facts suggest that Chanoki-daira lay in the top of the cloud which enveloped the lakeside and Akechi-daira. The standard deviations of the chronological change of the concentration were 8.3/cm³, 4.4/cm³ and 5.3/cm³ at the lakeside, Akechi-daira and Chanoki-daira respectively. These values of standard deviation are very small compared with those of the clouds in later stages and suggest that the cloud was in a quasi-stationary state.

In the second stage, 1200–1400 J.S.T., a high concentration with violent fluctuation arose at the lakeside. The peaks of concentration came around 1200 J.S.T. and 1300 J.S.T., the maximum concentration and water content were 108/cm³ and 0.65 g/m³ respectively, while the averaged concentration and water content 44/cm³ and 0.30 g/m³ respectively. The standard deviation of droplet concentration became 29.6/cm³. In (b), one of the peaks came around 1200 J.S.T., while, as shown in (c) to (e), the 50 μm-droplets are few and both 100 μm- and 200 μm-droplets are still fewer. Around 1300 J.S.T. a high concentration with violent fluctuation arose again and the number of 50 μm-, 100 μm- and 200 μm-droplets increased gradually, while the beginning of the increase was delayed with the growth of droplet size. The 100 μm- and 200 μm-droplets reached the peaks 1400 to 1425 J.S.T. These numbers decreased quickly after reaching the peaks. Especially, the 200 μm-droplets disappeared as soon as the 100 μm-droplets started decreasing. On the other hand, the droplet concentration at Akechi-daira began to increase monotonously and turned to a stationary state around 1230 J.S.T. as shown in (e). The averaged concentration and water content were 44/cm³ and 0.22 g/m³ and the maximum concentration and water content were 65/cm³ and 0.23 g/m³ respectively. The standard deviation of the concentration is 13.8/cm³. At Chanoki-daira, the concentration increased also in this stage and the averaged concentration was 18/cm³ with the standard deviation of 13.8, but the water content was still about 0.03 g/m³. It is clear that such larger cloud droplets at the lakeside did not originate in the upper part of clouds because such larger droplets did not appear at Chanoki-daira which is 300 m above from the lake side in the stage.

Another high concentration with violent fluctuation, maximum concentration 180/cm³, maximum water content 0.58 g/m³, arose at Chanoki-daira just after the fluctuation settled down at the lakeside. The third stage is characterized by the high concentration at Chanoki-daira after about 1400 J.S.T.. The averaged concentration
and water content at Chanoki-daira were 101/cm³ and 0.25 g/m³ respectively. In this stage, the averaged concentration and water content at the lakeside were 55/cm³ and 0.27 g/m³ respectively, but, the standard deviation of the concentration became 13.8/cm³ and the fluctuation became rather weak. At Akechi-daira, the averaged concentration, water content and standard deviation were 45/cm³, 0.20 g/m³ and 21.0/cm³ respectively. The 100µm- and 200 µm-droplets at the lakeside began to appear again after about 1420 J.S.T. and they reached the peaks around 1430 and 1505 J.S.T.. The 100 µm- and 200 µm-droplets were produced at the rate of 30/min and 20/min respectively.

The drizzle began around 1620 J.S.T. and turned into a heavy shower shortly after.

In the second and third stages, it is remarkable that the larger cloud droplets exceeding 200 µm are generated in a relatively short period, whenever a violent fluctuation of high concentration of droplet arises. The quick increase of the droplet concentration may suggest that some new cloudy thermals have developed around the observation site and the violent fluctuation indicates the mixing between the cloud air and surrounding dry air. The cloudy thermal developed and rose gradually to higher levels.

4.2 The size spectrum of cloud droplets in every stage

In the previous section, the observation period was divided into three stages characterized by droplet concentration. In this section, the size spectrum will be discussed in detail. The averaged spectra of the three sites in every stage are shown in Figs. 3-5, and comparison among the spectra in every stage at the lakeside, Akechi-daira and Chanoki-daira is shown in Figs. 6-8. In these figures, the symbols of abscissa 5, 10, 15, ... correspond to the diameter of droplet 0<D<5 µm, 5 µm<D<10 µm, 10 µm<D<15 µm, ... respectively.

4.2.1 The size spectra of cloud droplets the first stage

Fig. 3, which gives the averaged size spectra in the first stage, shows that the spectra at the lakeside and Akechi-daira are almost similar to each other and these show considerably broader and lower concentration than the general orographic cumuli. Furthermore, the standard deviation of the concentration is very small and the clouds are quasi-stationary as pointed out in the previous section. These facts may suggest that the activity of convection is very weak in the cloud. As an example, the orographic cumuli at Mt. Fuji are compared with those at Akechi-daira in Fig. 9. The spectra at Mt. Fuji were obtained in developing cumuli at 2100 m above sea level on the Gotenba slope (2.8 Go). These cumuli began to develop around Shin-nigō about 300 m below the observation site and drifted while growing on the slope. The cumuli contained few droplets larger than 25 µm but numerous droplets less than 10 µm. They developed in a strong up-slope airflow and were observed in the developing stage under a strong up-slope airflow. The vertical wind velocity of the up-slope airflow will be in proportion to the wind velocity along the slope, superadded to that of the whole rising air parcel. Therefore, the supersaturation in the cloud parcel increases and clouds containing numerous smaller droplet are formed as the wind velocity along the slope becomes larger. In Fig. 9, the averaged wind velocity is shown by the side of each spectrum, and it is shown that the number of droplets smaller than 15 µm
increases as the wind velocity becomes large. On the other hand, as to the quasi-stationalys cloud observed in the first stage at Nikkō, our consideration is as follows;

The orographic cumuli are developed in a slowly rising air parcel at first, but when these clouds pass through the mature stage, the smaller droplets will tend to disappear by evaporation and in the final stage turn into clouds containing only relatively large droplets. They drift with the general airflow of the cloud level and combining with each other make a colony of clouds like stratocumulus as they approach the mountain slope. After that, the colony slowly drifts up the slope with the up-slope airflow and maintains a slight supersaturation, which will be useful to the growth of the larger droplets. We can very often see that such a colony of clouds envelops the upper half of a mountain. BEST (1950) shows that droplets of 15 \( \mu \text{m} \) condensed on the sea salt nuclei of \( 10^{-14} \text{ g} \) which may be considered common hygroscopic nuclei can grow into droplets of 30 \( \mu \text{m} \) in about 30 min under supersaturation of 0.05%.

From these considerations, we can say that the lakeside and Akechi-daira were enveloped with a colony of dissipated cumuli in the first stage, and their depth is estimated as several hundred meters or less from the spectrum at Chanoki-daira.
4.2.2 The cloud droplet-size spectra in the second and third stages

In the second stage, 1200 to 1400 J.S.T., the droplet concentration quickly increased with violent fluctuation at the lakeside as shown in Fig. 2. At Akechi-daira, too, the concentration increased but it soon reached a stationary state and no violent fluctuation appeared. We can compare the spectra in the second stage with those in the first stage in Figs. 6–8. At the lakeside and Akechi-daira, the concentration of the droplets in the range of 15-25 \( \mu \text{m} \) increased remarkably as compared with the first stage; namely, the increasing of the concentration at both sites was mostly contributed by the smaller droplets of 15–20 \( \mu \text{m} \). On the other hand, the spectrum at Chanoki-daira was kept almost unchanged. Comparison among the spectra at the three sites in the second stage is shown in Fig. 4, which shows that the densest cloud enveloped the lakeside.

In the third stage, 1400 to 1500 J.S.T., the other clouds grew around Chanoki-daira soon after the developing of clouds abated at the lakeside. Size spectra in this stage are shown in Figs. 5–8. At Chanoki-daira, the number of cloud droplets increased extremely and especially we should note that the size spectrum became immediately similar to that at Akechi-daira in the range larger than 20 \( \mu \text{m} \) as shown in Fig. 5. The quick increase with violent fluctuation of the concentration of smaller droplets suggests the development of new cloudy thermals, but droplets larger than 25 \( \mu \text{m} \) are usually unable to grow on general hygroscopic nuclei in such a short time. In Figs. 6–8, it is interesting to note that the number of droplets increased for all sizes at the lakeside and Chanoki-daira, where a quick increasing of the concentration occurred with violent fluctuation, while droplets larger than 20 \( \mu \text{m} \) kept unchanged through all stages at Akechi-daira, where the concentration increased monotonously, turning to stationary soon after.

The facts mentioned above indicate that the appearance of the larger droplets is connected with the development of new cloudy thermals for some reason, while they can not be produced by condensation on common hydroscopic nuclei in such a short time. One of the reasons may be consider as follows;

The areas around the lakeside and Akechi-daira have already been enveloped with clouds containing larger droplets since the first stage. We will call the clouds as proto-cloud hereafter. If other and new cloudy thermals are developed in the proto-cloud, they are developed actively as pointed out by Mason and Emig (1961) and some larger droplets in the proto-cloud are carried up together with the smaller droplets in the thermals to upper levels. Therefore, the mixing cloud of the proto-clouds and the new cloudy thermals has a microstructure composed of the proto-cloud and the new cloudy thermals, namely the spectrum becomes a broader one with a relatively high concentration of smaller droplets. In the mixing cloud, the larger droplets which were carried up to higher levels can quickly grow by coalescence process, because they come down to the ground through the layer of numerous smaller droplets when the updraught of the mixing cloud weakens. The cloud parcels are developed successively and gradually rise to higher levels. Then the mixing cloud increases in depth and a greater number of larger droplets occur pulsationally whenever the cloudy thermal is developed. According to Mason’s calculation (1952), when one larger droplet of 40 \( \mu \text{m} \) in diameter
fall about 500 m in a cloud layer whose water content is 0.4 g/m³, it grows into a droplet of 150 μm.

Such process of production of the larger droplets may play an important role in precipitation from shallow orographic cumuli.

4.3 Size spectrum of the drizzle droplets

In previous sections, it was pointed out that 100 μm- and 200 μm-droplets were generated in a relatively short time, whenever new cloudy thermals developed. This was explained by the idea of mixing between the proto-cloud and the new developing cloudy thermal. There were two periods in which the 200 μm-droplets appeared remarkably as shown in Fig. 2: i.e. 1400–1435 J.S.T. and 1440–1505 J.S.T.. The former is related with the developing of cloud parcels around the lakeside and the latter with that around Chanoki-daira. The averaged size spectra of droplets larger than 50 μm were made from the samples of MgO film (24 × 36 mm²). We could find the large drizzle droplets exceeding 300 μm in the samples at 1410, 1415, 1420 and 1425 J.S.T., but we could not recognize such large droplets in the samples at 1400, 1405, 1430 and 1435 J.S.T. namely, such drizzle droplets occurred in a short time. The drizzle droplets exceeding 300 μm appeared at the ratio of 0.1 per liter or more at maximum value. The averaged size spectrum of the samples at 1410, 1415, 1420 and 1425 J.S.T. is shown with full circles and that at 1400, 1405, 1430 and 1435 J.S.T. with open circles in Fig. 10.
The spectra of droplets less than 50 \( \mu \text{m} \) in the same period are also shown in the same way in Fig. 11. The sampling area of MgO film was about 0.5 \( \times \) 0.3 cm\(^2\) in this case. The spectra in the period 1440-1505 J.S.T. are also shown in Figs. 12 and 13. In this period, drizzle droplets larger than 300 \( \mu \text{m} \) appeared only in 1500 and 1505 J.S.T.. These figures indicate that the concentration of droplets less than 100 \( \mu \text{m} \) remained nearly unchanged in a cloud with precipitation, but that of drizzle droplets exceeding 100 \( \mu \text{m} \) varied with the activity of the convection in the cloud thermal.

It is interesting to note that the droplets concentration in Fig. 13 considerably decreases in the range of 15-30 \( \mu \text{m} \) compared with the averaged spectrum over the third period as shown in Figs. 6 and 7. The fact suggests that such droplets were actively rain out from the cloud by the drizzle droplets which were produced in developing cloudy thermal at higher levels.

5. Conclusions

From our observations, the process of the formation of a shower in a shallow orographic cumulus can be deduced as follows: First, a proto-cloud containing some larger droplets exceeding about 30 \( \mu \text{m} \) appears before orographic cumuli are developed. In the next place, cloudy thermals develop in the proto-cloud and gradually rise to higher levels. The thermal developed in the proto-cloud carries up the larger droplets in the proto-cloud together with numerous small growing droplets to higher levels. Then the growth of such larger droplets may be accelerated in the new thermals because the larger droplets are carried up and fall down through the layer of numerous smaller cloud droplets. It may be thought that the mixing between the proto-cloud and new developing
cloud parcel plays an important role for the formation of precipitation in shallow orographic cumuli. Therefore, it is not always necessary to appeal to the condensation on giant sea salt nuclei.

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References

降水を伴う地形性小積雲の雲物理的性質の研究
佐藤純男, 徳植 弘

内陸の山間部に発達する地形性小積雲の中に、降水をおこし易いものがある。例えば日光周辺に発達する夏季の小積雲は、Drizzle を伴う、しばしば激しい Shower をおこす。積雲の高さからみて、これらの降水は、warm rain type のものと考えられる。このような積雲は、一般風が 30 cm/s 程度の弱いときに発達し、雲の移動はおそい。

ここで、このような、地形性小積雲について、その発生時から Shower を降らせるまでの雲粒分布の変化及びその間の大積雲の発生のありさまを観測し、地形性積雲への降水機構を推定した。

観測は1966年9月12日に行なった。観測点は第1図に示す通り、中禅寺湖の東岸（海拔1,300m）、明智平（1,200m）及び茶の木（1,620m）とした。

観測項目は MgO フィルムによる雲粒観測主にした。雲粒採取方法は、MgO フィルムを水平におき、自然落下する雲粒を採取した。雲粒の採取時間は2～3分おきである。その他、湖畔観測点では、吾々が開発したリーク方式の大積雲計（1969、佐藤）と Transmissometer の観測も同時に行なった。

結果は第2図以下に示してある。これによると、観測点が雲におおわれてから Shower までに、雲は3つの特徴ある微細構造の変化を示した。即ち、11h30m～12h00m では、湖畔、明智平共に直径30μm 以上の雲粒を含む、比較的空洞密度も小さい雲におおわれた。このとき、約300m 上の茶の水平では、空洞密度の非常にうすい雲しかかかっていなかった。これらの事から、この時期には、観測点附近は雲厚、数百米程度の比較的一様で大粒の雲粒を含む、雲におおわれていたと言えよう。

次に、12h00m～14h00m には、湖畔で、激しい変動を伴なう雲粒空間密度の急増が起きた。これに伴ない、13h30m 頃から100μm 以上の Drizzle 粒子が顕著的に、大積雲計に表われ始めた。併しこの変動が止むと、Drizzle の出現も止まった。明智平でも、殆ど同時に雲粒密度の増加が見られたが、すぐに定常状態に達し、湖畔のような、激しい変動は、おきなかった。又茶の水平では、雲粒密度が幾分増加した程度で殆ど前と変わらない状態が保たれた。従って、この時の Drizzle は茶の水平より上方の雲から降ってきたものではなく、湖畔附近に新らしい積雲が発達したために出来たものと考えられる。湖畔における雲粒濃度の変動が弱まると、今度は、更に激しい変動が、300m 上の茶の水平におおかった。このとき茶の水平の雲は30μm 以上の雲粒を含み、高濃度の雲粒分布になった（14h00m～15h00m）。この時も、湖畔の大積雲計に100μm以上の Drizzle 粒子が再び現われた。明智平の MgO にも同様 Drizzle 粒子が現されてきていて、15h00m 以後激しい Shower がおこり観測を中止した。

以上の事から、今度の降水は、まず、30μ 以上の雲粒を含む雲が現われ、その雲の中、あるいはぐく近くに、新らしい積雲が発達し、前からあった、30μ 以上の大粒の雲粒を上層にもあがる。これらの大粒子はより高い過飽和度、雲粒濃度のもとで、成長が促進され、雨滴に成長して落下したことを暗示している。そして、このような新らしい積雲活動は、順次上層に達し、だんだん大きな雨滴を降らすものと考えられる。