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The Cloud-base Topography and Formation Condition of Cumulus Humilis Clouds

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Abstract

The cloud-base topography of cumulus *humilis clouds* over the mountainous terrain and the nearby plain area was measured by the stereo-photogrammetric method in the summer seasons of 1969 to 1971 near Sapporo.

As a result of analysis, it was noted that the height of the base of cumulus humilis clouds over the mountainous terrain was considerably higher than that over the lower plain. The result showed also that the height of cloud base coincided with that of lifting condensation level which was calculated from Henning's formula.

The difference in the height of cloud bases over the mountainous terrain and over the lower plain area was quantitatively explained, utilizing the difference in the potential temperature and dew point at these two places. It was finally concluded that the excess height of cumulus humilis cloud base on the mountainous terrain over that on the lower plain area was mainly caused by the dryness of an air layer around 300 m altitude above sea level.

The formation condition of cumulus humilis clouds was studied, comparing with those of stratiform clouds and cloudless sky.

I. Introduction

At times the height of cloud base at a place is estimated from the lifting condensation level nearby, because it is considered that the height of the condensation level is uniform in an area. And frequently the height of cloud base is estimated from the height of lower exposed portion of a mountain whose top is covered by a cloud layer. However, according to MacCready's estimation[1], in mountain-valley areas, the bases of hill-formed clouds were higher than valley-formed cloud bases by one-half of the hill-valley elevation difference. Orville[2] also indicated that the cloud bases over the higher terrain was higher than that over the lower terrain, however neither quantitative data nor detailed explanations were given in his paper.

When the authors[3] observed the humilis clouds by the stereo-photogrammetric method in the summer seasons of the years of 1969 to 1971 near Sapporo, they noticed that the height of base of the clouds over the mountainous terrain was much greater than that over the nearby plain area. This paper is mainly dealing with the cloud-base topography of the cumulus humilis clouds.

The observation and analysis methods were the same as described in the paper[2]. The error margin in the observation of cloud height was estimated as about 100 m. In the analysis, surface meteorological data at Koganeyu were used as a representative condition in the mountainous terrain. The Koganeyu Observations Site for Agriculture is 280 m high above sea level. As the representative condition in the lower plain area, data obtained by Sapporo Meteorological Observatory with altitude of 50 m and Okadama Airport Observatory near Sapporo City were used. The location of these observation sites are shown in the left side of Fig. 1.

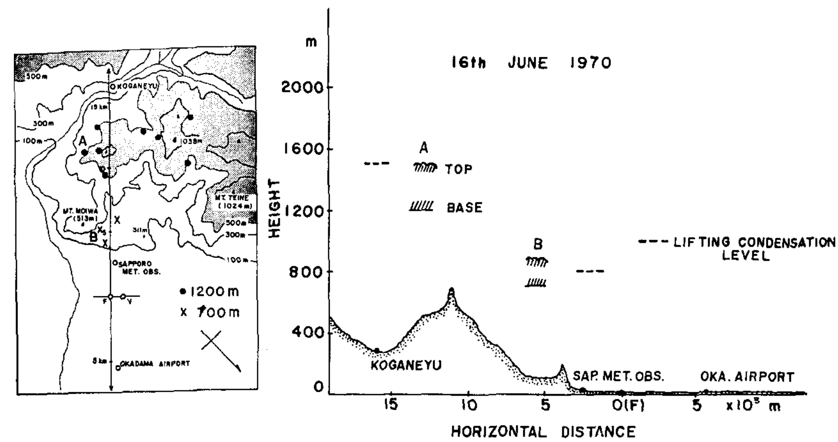

Fig. 1 Locations of clouds over higher terrain (●) and lower terrain (×) on June 16, left, and heights of clouds A and B, and lifting condensation levels, and vertical cross section of topography along the camera axis from site F, right.

2. Observation result

Totally 20 cases of cumulus humilis clouds were observed and analyzed in 1970 and 1971. From those cases, four of the cases were particularly considered, because in these cases, cumulus humilis clouds were observed both over the mountains and over the lower plain.

One of a pair of stereophotographs of cumulus humilis clouds is shown in Figs. 2a and 2b. They were taken at 0834 and 0856 (JST) on June 16, 1970, respectively. Marks A and B in the figures indicate remarked clouds.

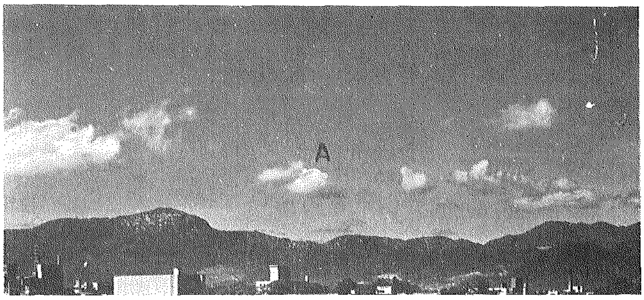

Fig. 2a Cumulus humilis cloud A over higher terrain, 0834 June 16, 1970.

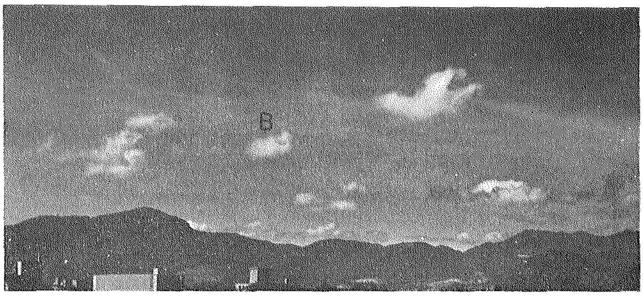

Fig. 2b Cumulus humilis cloud B over lower terrain, 0856 June 16, 1970.

According to the stereoscopic analysis, cloud A was over a higher portion of mountain and cloud B was over a lower portion. near Sapporo. The horizontal position of clouds A and B is shown in the left side of Fig. 1. On the right side of the figure, the vertical crosssection of the topography along the camera axis from observational site F near which clouds A and B were located. The vertical axis shows the height above sea level.

The height of cloud top and base is shown in the figure. It will be seen that cloud A over the mountain is considerably higher than cloud B over the foot of the mountain. The lifting condensation level at Sapporo and Koganeyu was calculated from Henning's formula $H=125\ (T-T_d)$, where H is the height of lifting condensation level in meter, T and T_d are the air temperature and the dew point temperature in °K, respectively. The height of the condensation level is shown by a broken line in the figure. It is seen that the condensation level at Sapporo agrees well with the observed cloud base of B. However, the condensation level at Koganeyu was somewhat higher than the cloud base over the mountainous terrain.

Fig. 3a Cumulus humilis clouds over mountains, 0850 Sept. 13, 1970.

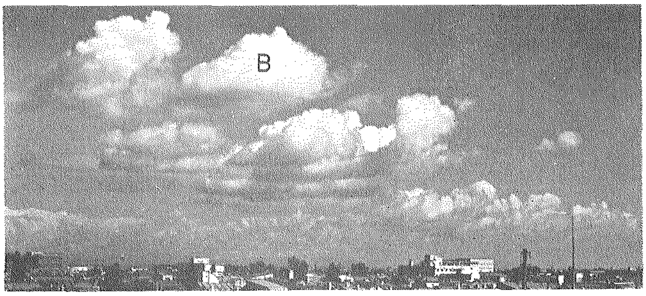

Fig. 3b Cumulus humilis clouds over Ishikari Plain, 0937 Sept. 13, 1970.

Figs. 3a and 3b show another example. Cloud A in the upper photograph was over the mountain side, and cloud B in the lower one was over the plain. The height of these two clouds with respect to the topography is shown in Fig. 4. It will be seen that the base level of cloud A over the mountainous terrain is higher than that of cloud B over the plain. It is also seen that the condensation level at Koganeyu is inagreement with the cloud base over the mountainous terrain, and the condensation level at Sapporo or Okadama well agrees with the cloud base over the plain area.

Besides the examples, the remaining other cases were also analyzed. All the results are listed in Table 1. It will be seen in the table that the observed height of cloud bases on the plain well coincides with the condensation level which calculated from the data at Sapporo. Similarly, the observed cloud bases over the mountainous terrain also approximately coincide with the condensation levels which calculated from data at Koganeyu, although in this case the cloud bases were slightly lower.

The mean values of height of cloud bases on June 16, July 2, Sept. 11 and

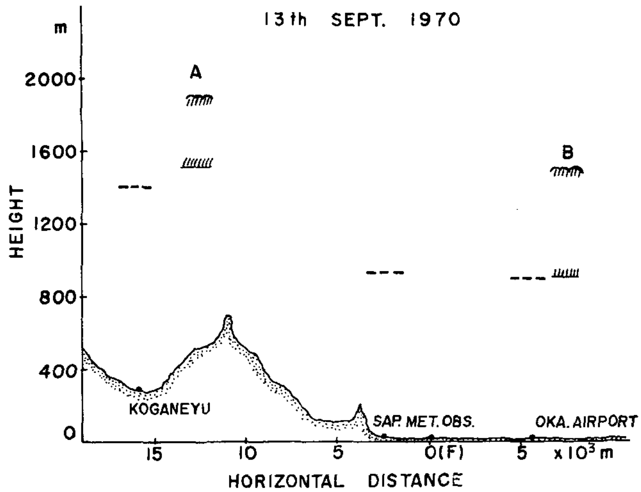

Fig. 4 Heights of clouds *A* and *B*, and condensation levels on Sept. 13.

Table 1. Comparison of lifting condensation level with observed height of cloud bases. Dashed under lines show that cumulus humilis clouds occurred on the day both over mountains and over plain.

Date	Cond. level at Koganeyu (m)	Cloud base over Mts. (m)	Cond. level at Sapporo (m)	Cloud base over plain (m)
(1970)				
16 June	1500	1200	800	700
24	1400	—	800	900
27	1100	—	700	600
29	—	—	800	900
2 July	1200	1200	700	800
7 Sept.	—	—	1500	1700
11	1900	1800	1400	1500
13	1400	1500	900	900
14	1600	—	1200	1300
19	1500	1500	1200	—
20	1700	1700	1700	—
24	1500	1400	1100	—
27	2100	1900	1400	—
11 Oct.	—	—	1400	1300
(1971)				
28 Aug.	1000	—	700	600
6 Sept.	1400	1500	700	—
15	—	—	1200	1400
Mean of 16 June, 2 July, 11 and 13 Sept., 1970		1420		970

13 are shown at the bottom of the table, because only on these days, cumulus humilis clouds occurred both over the mountains and over the plain. Comparing these values, it is seen that the cloud base over the mountains was 450 m higher than that over the plain on the average.

3. Discussion

In the case of stratiform clouds, it is usually said that the height of cloud base over the mountainous area is nearly the same as that over the nearby plain. However this was not the case in the cumulus humilis clouds as described before. The authors, therefore considered the reason why the cloud base of cumulus humilis clouds over the mountains was higher than over the plain.

If the air is transported from a plain toward a nearby mountain and slide up its slope adiabatically, the condensation level over the mountain will be the same as that over the plain. Therefore the wind direction on those days of cumulus humilis clouds was surveyed. The frequency distribution of prevailing surface wind directions at Sapporo and Koganeyu on the days of cumulus humilis clouds are shown on the left and right sides of Fig. 5, respectively. The wind directions are expressed in the eight-compass points. It is seen in the figure that during the day of cumulus humilis clouds, the easterly and southeasterly winds were generally predominant in both the mountain terrain and the plain area. This shows that the wind were blowing in parallel to the mountain ridge in the south-west side of Sapporo, in other

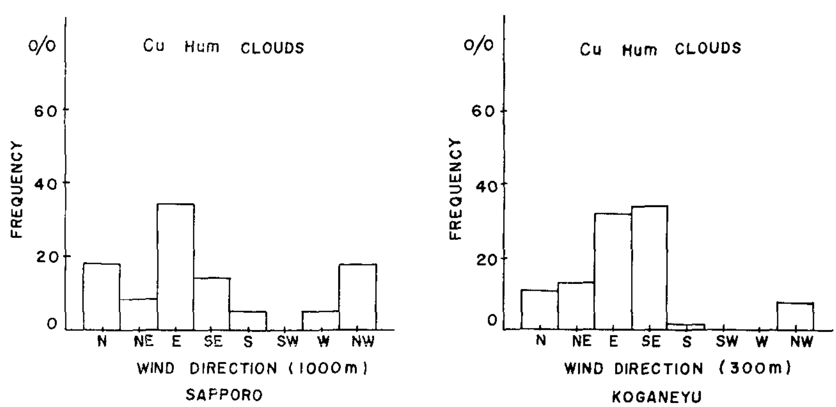

Fig. 5 Frequency distribution of wind direction at Sapporo and Koganeyu during days of cumulus humilis clouds.

words there was not wind component to cross the mountain ridge. Because the wind did not slide up the mountain slope on the day of cumulus humilis clouds, it is, therefore considered that the condensation level on the mountain can be different from that on the plain.

In the case of flat topography, the height of cloud bases was represented by the condensation level which calculated from the data at the surface, as shown in Table 1. In case of mountainous area also, this was roughly the case. If the cloud base can be represented by condensation level, the data which collected in 1969 are available for the discussion of difference in the cloud bases between over the mountain and over the plain, although the height of cumulus humilis cloud base was not measured in 1969.

The scatter diagram of lifting condensation level on the days of cumulus humilis cloud is shown in Fig. 6. In the figure, the vertical axis and horizontal axis represent the height of condensation levels above sea level at Koganeyu and Sapporo, respectively. The data in 1969 are also included in the figure. The 45° angle line is entered in the figure for convenience of comparison. It is clearly seen that the height of lifting condensation levels

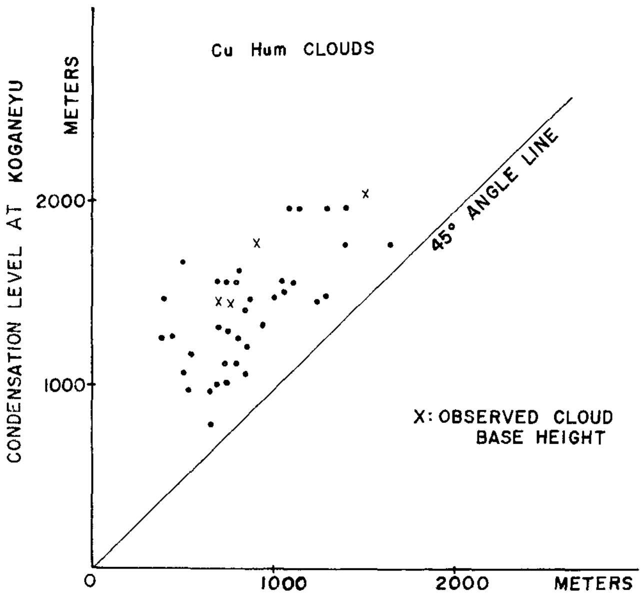

Fig. 6 Scatter diagram of condensation level at Sapporo vs at Koganeyu during days of cumulus humilis clouds.

above sea level at Koganeyu are considerably greater than those at Sapporo.

As shown in Henning's formula, the lifting condensation level is described by the difference between air temperature and dew point temperature at the surface of ground in question. Therefore the air temperature and dew point temperature on Koganeyu and Sapporo were considered, in order to consider the difference in the condensation levels between the mountain and the nearby plain. However because the altitude of Koganeyu is 230 m higher than Sapporo, the potential temperature and mixing ratio on these places, instead of the factors were compared, in order to avoid the effect due to the difference in altitude, as seen in Figs. 7 and 8. It will be seen in the figures that the potential temperatures at Koganeyu are higher than those at Sapporo, while the mixing ratios at Koganeyu are lower than those at Sapporo. Hereinafter all the heights are converted to those above 1000 mb level.

The mean value of lifting condensation levels above 1000 mb level, potential temperature, mixing ratio and dew point which converted to 1000 mb level, during the day of cumulus humilis clouds at Koganeyu and Sapporo

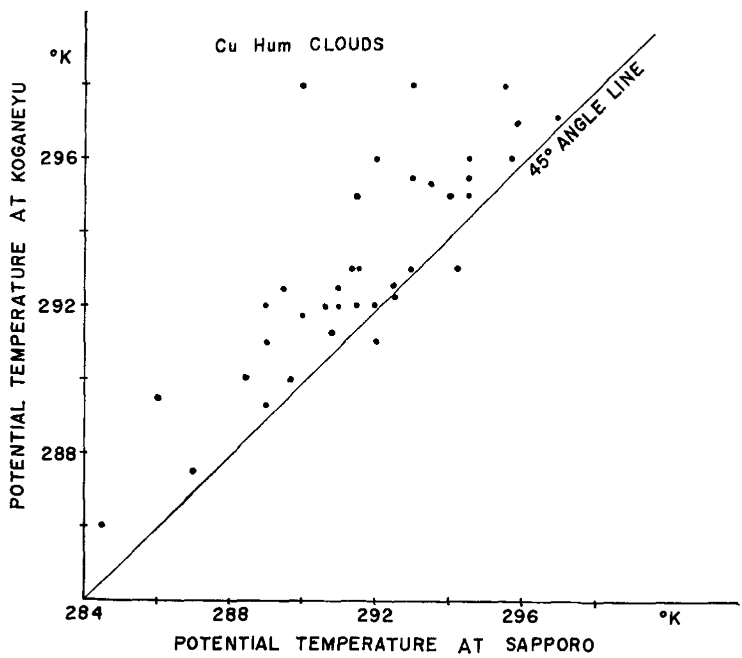

Fig. 7 Scatter diagram of potential temperature at Sapporo vs at Koganeyu during days of cumulus humilis clouds.

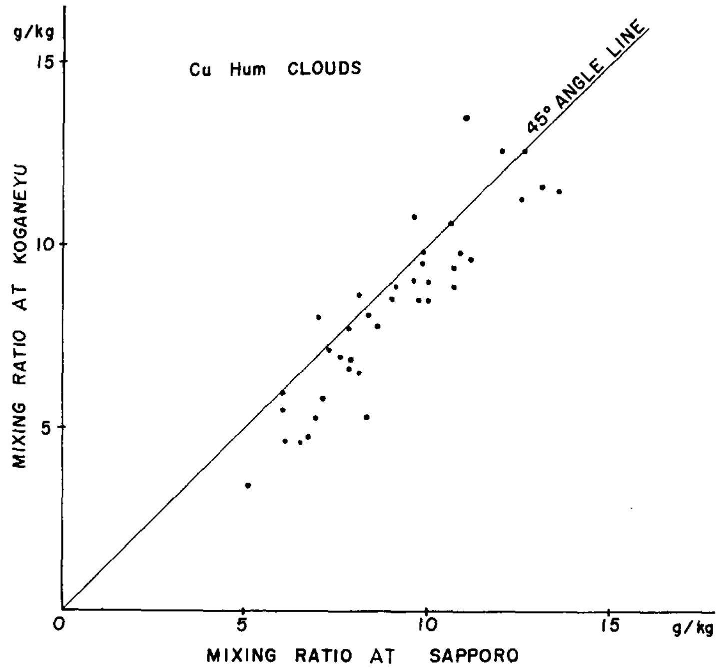

Fig. 8 Scatter diagram of mixing ratio at Sapporo vs at Koganeyu during days of cumulus humilis cloud.

are listed in the left side of Table 2.

In the table, the differences of those quantities are given in the fourth line, and the contributions of potential temperature and dew point to the condensation level are shown at the bottom of the table. It will be seen that the condensation level at Koganeyu is 410 meters higher than that at Sapporo. This value roughly coincides with the mean value: 450 m of cloud base excess of the mountainous terrain over that of the plain area, as shown in Table 1. It is also noted in Table 2 that the contribution of humidity to the condensation level is greater than that of potential temperture. It is clear that the air at Koganeyu was fairly dry, compared with that at Sapporo on the day of cumulus humilis clouds.

The potential temperature excess at Koganeyu over at Sapporo was 1.4°C. This value is considerably greater than expected from the difference in the altitudes of Koganeyu (280 m) and of Sapporo (50 m). This may be caused by the dry adiabatic subsidence of air from the upper layers on those days of

Table 2. Mean values of heights of condensation levels above 1000 mb level, potential temperatures, mixing ratios, and dew points during days of cumulus humilis clouds and stratiform clouds.

Places	Cu humilis clouds				Stratiform clouds			
	Cond. level (m)	Potential temp. (°K)	Mixing ratio (g/kg)	Dew point (°K)	Cond. level (m)	Potential temp. (°K)	Mixing ratio (g/kg)	Dew point (°K)
Koganeyu	1140	293.1	8.3	284.0	590	292.9	10.8	288.2
Sapporo	730	291.7	9.1	285.9	330	291.2	10.9	288.6
Difference	410	1.4	−0.8	−1.9	260	1.7	−0.1	−0.4
Contribution to cond. level		170 m		240 m		210 m		50 m

such cumulus humilis clouds, because the cumulus humilis clouds usually occurred under a synoptic condition where the area is covered by an anti-cyclone.

For comparison, the authors considered the condensation level on the day of stratiform clouds. The mean values of condensation level, potential temperature, mixing ratio and dew point on the day of stratiform clouds during the season of the observation are shown in the right side of Table 2. It is seen that the condensation level at Koganeyu is higher than at Sapporo on the average, but the difference is only at half of the case of cumulus humilis clouds. This fact is consistent with the usual experience.

It is also noted that the contribution of humidity to the condensation level was negligibly small, compared with that of temperature. The great excess of potential temperature at Koganeyu over Sapporo may be also caused by the subsidence of air in the stable condition so that stratiform clouds occurred near the surface in the morning of summer season.

By comparing the condition of cumulus humilis clouds with that of stratiform clouds, it is considered that the low humidity at Koganeyu is important to make the condensation level at Koganeyu higher.

As described above, in the case of cumulus humilis clouds, the air at the surface level of Koganeyu was dryer than that at Sapporo. It is, therefore interesting to check the cause of the low humidity at Koganeyu. Table 3 shows the mean mixing ratios at surface, 300 and 500 meter altitudes on the day of cumulus humilis and stratiform clouds. The altitude of

Koganeyu is nearly 300 meters. The figures in parentheses in the table show the mean mixing ratio at Koganeyu. It is seen that the mixing ratio at Koganeyu is almost equal to that of the free air at 300 meters altitude over Sapporo both in cumulus humilis clouds and in stratiform clouds. This shows that the meteorological conditions at Koganeyu are determined only by the height above sea level and not by any local moisture conditions. Therefore, it is generally said that in the case of cumulus humilis clouds, the air between 300 and 500 m altitudes was considerably dry as compared with the case of the stratiform clouds.

Table 3. Mean mixing ratio over Sapporo, at surface, 300 m and 500 m.

Cloud type	Mean mixing ratio over Sapporo (g/kg)		
	Surface	300 m	500 m
Cu humilis clouds	9.1	8.4 (8.3)	8.0
Stratiform clouds	10.8	10.5(10.8)	10.2

( ): Mean mixing ratio at Koganeyu

In the present case, the hill-formed cloud bases are higher than the plain-formed cloud bases by two times the hill-plain elevation difference. It is probable that the difference between the results of MacCready's study and the present one was caused by the humidity distribution, however the humidity given in MacCready's paper[1)] is not in detail to compare with the present data.

4. Climatological conditions for the formation of cumulus humilis clouds

In the section above, it was shown that the dryness around 300 meter altitude was a characteristic property of the cumulus humilis clouds. The authors, further surveyed the general climatological condition for the formation of this kind of clouds.

It is well known that cumulus humilis clouds form under certain background conditions which are closely related to the weather system. Theoretical studies and observations show that the thermal stability of air and the relative humidity at the lower part of the atmosphere exert a pronounced influence on the formation of cumulus clouds.

In the present study, it was, at first tried to find the relationship of the thermal stability and the relative humidity with the formation of cumulus humilis clouds, stratiform clouds or cloudless skies in the lower atmosphere from the ground to 900 mb level. The thermal stability of the lower atmosphere was represented by the temperature lapse rate. The relative humidity was averaged from the ground to the 900 mb level in this study. All of these data used, were obtained from the radiosonde soundings made by the Sapporo Meteorological Observatory. The observation of cloud types was made by the authors.

The vertical distribution of lapse rates in the case of cumulus humilis clouds is shown in the right side of Fig. 9, in which the various curves show the monthly average on days when cumulus humilis clouds were observed. The years and months in which observations were made are indicated by arrows. It is clearly seen from the distribution of lapse rate that in the layer between ground and 900 mb level, the lapse rate is commonly large, in other words, it means that the layer was nearly unstable. It is noted that the layer between 800 mb and 700 mb was considerably stable in all cases. It is considered that the existence of such a stable layer is the characteristic property of the lower atmosphere during the formation of cumulus humilis clouds.

The distribution of relative humidity is shown in the left side of Fig. 9.

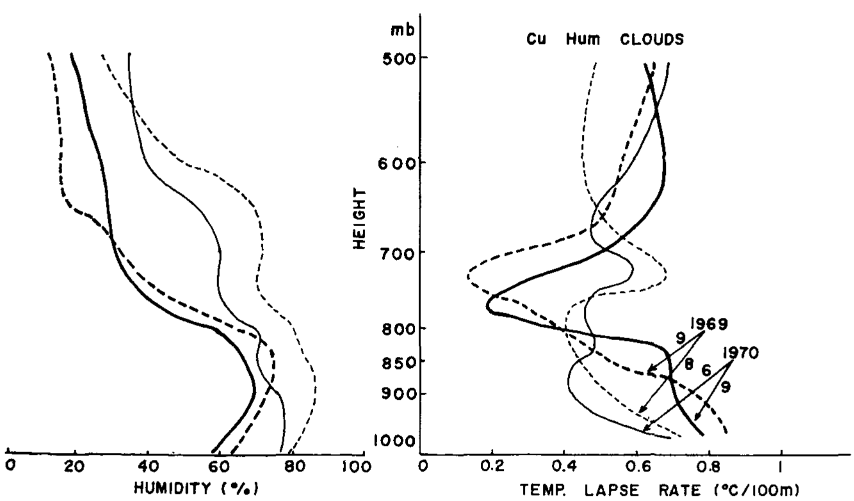

Fig. 9 Vertical distribution of mean temperature lapse rate and humidity during days of cumulus humilis cloud.

It is seen that the relative humidity below 800 mb level is generally higher than the level above, although the humidity just near the ground seems to be lower. This shows that in the case of cumulus humilis clouds, the air below the 800 mb level is moist and the upper layer is dry. This corresponds to the description at the top of this section.

For comparison, the vertical distribution of lapse rate and the distribution of relative humidity of cloudless sky are shown in the right and left sides in Fig. 10. It is immediately seen that in the case of choudless sky the lower atmosphere below 900 mb level was more stable than the upper layer. However the humidity in the lower layer was considerably low and gradually decreased with height. It is reasonalbe to infer that the cloudless sky was caused by the stable situation and low humidity in the lower layer near the ground level.

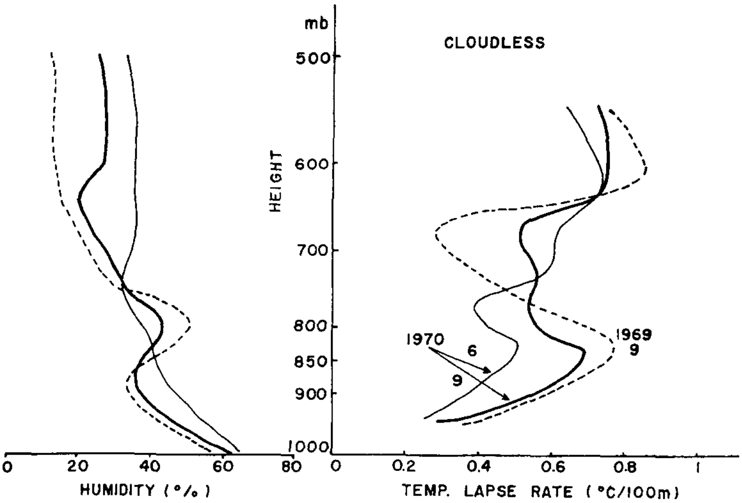

Fig. 10 Vertical distribution of mean temperature lapse rate and humidity during days of cloudless sky.

Fig. 11 shows the relationship of the lapse rate and the humidity in the layer between the surface and 900 mb level on the day of cumulus humilis clouds, stratiform clouds and cloudless sky. In the figure, the horizontal axis shows the mean lapse rate in the layer lower than 900 mb level for each cloud type. The vertical axis shows the relative humidity. The moist and dry adiabatic lapse rates are indicated by γ_m and γ_d on the horizontal axis

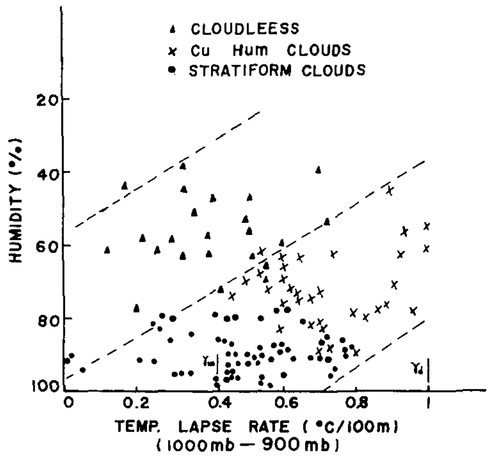

Fig. 11 Relationship of temperature lapse rate (1000–900 mb) and humidity during days of cumulus humilis cloud, stratiform cloud and cloudless sky. and show wet and dry adiabatic lapse rate, respectively.

of the figure. Triangle, cross and dot marks represent the data on the days with cloudless sky, cumulus humilis clouds and stratiform clouds, respectively.

It can be seen in the figure that the stratiform clouds were formed under a wide range of lapse rates from 0 to 0.8°C/100 m, and under a high humidity between 80 and 100%. In other words, the necessary condition for the formation of stratiform clouds is the moist air near the surface, disregarding to the lapse rate. While in the case of cumulus humilis clouds, it is seen that the lapse rate was in the range of about 0.6 to 1.0°C/100 m, and the humidity was of 60 to 80%. Namely both a high lapse rate and a moderately moist air layer near the surface are required for the formation of this type of clouds. Besides these, a dry air layer around 300 meter altitude is required as described in Section 2. The points for cloudless sky are scattered in the left side above the area representing the formation condition of other two types of clouds. Namely, the lapse rate was small and the humidity was also low. This is a matter of course.

Concluding remarks

It was observed that the height of cloud bases over the mountainous terrain was considerably higher than that over the lower plain, although it is thought that the condensation level on the mountain area is the same as that over the nearby low plain area. The difference was partially explained by considering the difference in the potential temperature in these two areas, however it was concluded that the main reason was the existence of dry air layer around 300 meter altitude when the cumulus humilis clouds were formed.

Here, the authors would like to point out that we should be careful in estimating the height of condensation level over the mountainous, utilizing the height of condensation level over the nearby plain.

It may be possible to estimate the conditions for the formation of cumulus humilis clouds, stratiform clouds and cloudless sky from the diagram in Fig. 11. However the diagram is too simple. It is hoped that formation conditions of other kinds of clouds, such as cumulus congestus, cumulonimbus, fog etc. will be added. It is also hoped that such a study as including a quantitative analysis will be conducted in the near future.

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