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Simultaneous Aircraft Observations of Aerosol and Cloud Droplet Concentrations Related to Global Cooling

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Abstract

Aircraft observations were carried out in order to study the relationship between aerosol concentration and cloud droplet concentration as basic research on the indirect effect of aerosol. We analyzed data for clouds that satisfied two standards: clouds of measured aerosol concentrations but without precipitation. The results showed the horizontal and vertical structures of clouds, which can be characterized as follows. The maximum values in cloud droplet concentration and liquid water content are located at the center portion of cloud. Also, cloud droplet concentrations show nearly equal values regardless of the height, and the liquid water content increases with increasing height. The relationship between the aerosol concentration under the cloud base and the cloud droplet concentration in the clouds is represented by the regression formula $Y=178X^{0.26}$, which asserts that the rate of increase of the cloud droplet concentration in large aerosol concentrations is less steep than in small aerosol concentrations.

1. Introduction

Global cooling caused by the increase of aerosols is an important process in global climate change as well as in the greenhouse effect of CO_2. Atmospheric aerosols exert both a direct and an indirect force on climate. The direct force is the direct scattering and absorption of sunlight by aerosols in clear air. The indirect force is that man-made cloud condensation nuclei, through changes in cloud microphysics, would potentially modify cloud albedo. This indirect forcing was proposed first by Twomey (1977, 1984) and called the Twomey effect. The Twomey effect plays an important role in maritime stratus, which covers a wide area and has a long lifetime (Charlson et al., 1992 ; Hudson, 1993). Sulfate aerosols play an important role because they increase the most likely cloud condensation nuclei, which are thought to promote the indirect effect (Léaitch et al., 1992). There is a great deal of uncertainty in our understanding of this effect and accurate estimates have not yet been obtained, because cloud droplet forming and chemical processes are combined in a complicated way. Namely, further understanding in the role of clouds is necessary to accurately estimate the global climate change.

The shortwave albedo, which is a very important parameter in radiative budget, increases with the increase of optical thickness. A cloud of depth h, containing cloud droplets at height z above the cloud base, possesses the optical thickness τ such that

$$\tau=\int_0^h K_E dz, \tag{1}$$

where K_E is the extinction coefficient. For solar wavelengths and for realistic drop distributions, we can eliminate the integration and adopt the simple formula

$$\tau=2\pi N\bar{r}^2 h, \tag{2}$$

where N is the cloud droplet concentration and $\bar{r}$ can be any representative mean or model radius (Twomey, 1977). It is convenient and sufficiently accurate to use the volume-mean radius so that the liquid water content W is given by

$$W=\frac{4}{3}\pi\bar{r}^3\rho_w N. \tag{3}$$

We eliminate the variables $\bar{r}$ or N from equations (2) and (3), and obtain

$$\tau\propto N^{\frac{1}{3}}W^{\frac{2}{3}}h \text{ or } \propto \bar{r}^{-1}Wh \tag{4}$$

Namely, if the cloud droplet concentration increases under the condition of fixed liquid water content and cloud depth, the cloud droplet mean radius decreases, but the optical thickness increases (e.g. If N is increased to $8N$, $\bar{r}$ decreases to $\bar{r}/2$ using equation (3), so τ increases to double). The optical thickness increasing eventually results in the increase of the shortwave albedo and in the reduction of sunlight to the surface of the earth. The purpose of this study is to clarify the relationship between aerosol concentration and cloud droplet concentration, which reflects the aerosol concentration on the right side of equation (4).

2. Observational and analytical procedures

Aircraft observations were carried out during the periods of December 10–19, 1999 and November 28–December 6, 2000. The purpose of these observations was to clarify the role of clouds on the transportation and transformation of air pollution materials which flow from the East Asiatic Continent to the Sea of Japan. Penetrating and horizontal flights were carried out in the interior and under the base of the stratocumulus and cumulus clouds which form over the Sea of Japan. Penetrating flights were carried out at only one height, because clouds were not very thick.

Observational areas were off the Oki Islands, as shown in Figs. 1 and 2. In 1999 four flights were carried out and each lasted three hours in flight time. Two of the flights took place during a northwest monsoon on December 17 and 19. In 2000 three flights were carried out on December 2, 3 and 5. The weather conditions for the flights in 2000 did not include the northwest monsoon, as in the 1999 flights.

The data were obtained using B-200 aircraft. The B-200 aircraft is equipped to measure GPS latitude, GPS longitude, altitude, flight speed and flight attitude. Also, a CCD camera recorded the clouds. Particle counters (RION KC-OIC; KANOMAX TF-500) and an aircraft microphysics probe

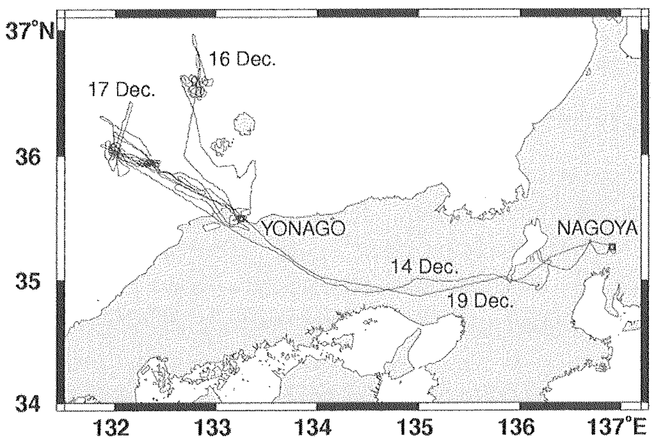

Fig. 1. Flight courses in 1999.

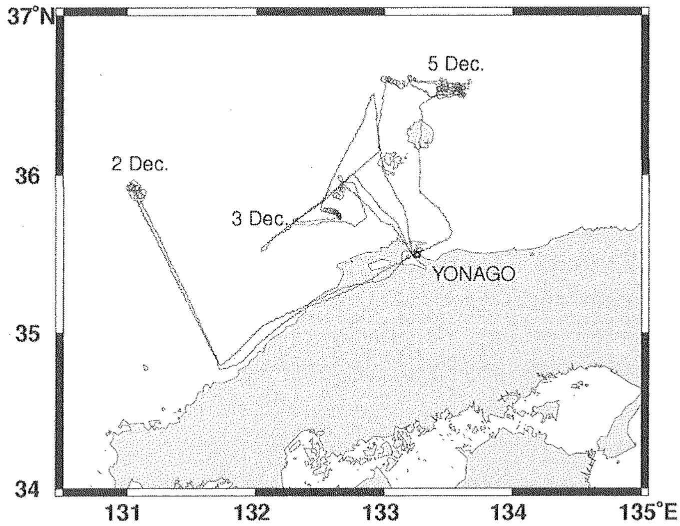

Fig. 2. Flight courses in 2000.

(Gerber Scientific Inc. Model PVM-100A) instruments were used to obtain the data on aerosol concentration and cloud droplet concentration, respectively. The particle counter can obtain the aerosol concentrations at more than 0.3, 0.5, 1.0, 2.0 and 5.0 μm in diameter, respectively. The aircraft microphysics probe can obtain the liquid water content, surface area and effective radius of the droplet size spectrum. Therefore, the cloud droplet concentration was calculated from the liquid water content and effective radius under the assumption that the shape of a cloud droplet is a sphere.

3. Results

3.1 Selection standard for analyzing object

Selection standards were set up to select the clouds suitable to analysis from the observed clouds as follows;

(1) clouds without precipitation,

(2) clouds for which aerosol concentration data were obtained during horizontal flights under the cloud base.

In the case of precipitation, it is difficult to find an accurate relationship between aerosol concentration activated at the cloud base and cloud droplet concentration due to reduction of cloud droplets collected by rain drops. Therefore, our analysis is limited to the clouds without precipitation. Clouds with or without precipitation were judged by the pilot report. In order to correspond the cloud droplet concentration with aerosol concentration under the cloud base, we selected the clouds with simultaneous measurements of both cloud droplet concentration and aerosol concentration.

After selecting an object of study, we identified each cloud. It was difficult to judge the rift in the cloud by only data of the liquid water content and cloud droplet concentration for the stratocumulus. Therefore, we confirmed the cloud aspect and the rift in the cloud using the picture taken by the CCD camera. When we could not confirm a cloud due to an unclear picture, we used the data of the liquid water content and cloud droplet concentration as confirmation. For example, we judged that cloud A and cloud B were separate, if there was a distance of more than 2 km between the two. Based on the method mentioned above, we judged synthetically. Using the above method, we identified twenty cloud samples : three samples on December 16, three samples on December 17 and four samples on December 19, 1999 : five samples on December 3 and five samples on December 5, 2000.

After identification of the clouds, the maximum value of cloud droplet concentration for each cloud was determined as representative values. The aerosol concentration, which corresponded with the cloud droplet concentration, was obtained by averaging the data obtained under the cloud base.

3.2 Horizontal structure of cloud represented by cloud droplet concentration and liquid water content

It is possible to evaporate the cloud droplets and reduce the concentrations and radii of cloud droplets at the edge region by mixing them with the outer air. In order words, it is thought that the cloud droplet concentrations observed at the edge region are possibly lower than the original concentrations. It is considered that cloud droplets are not affected very much by mixing and they keep adiabatic liquid water content at the central region as shown by shaded area in Fig. 3. The cloud droplets in the central region are thought to reflect the cloud droplet concentration generated at the cloud base. Namely, when studying the relationship between aerosol concentration under the cloud base and cloud droplet concentration in the cloud, penetrating flight, as shown by course (1) in Fig. 3, is preferable to that shown by course (2) in Fig. 3. But, actual observation is not necessarily always possible in course (1). So, we tentatively adopt the maximum values of cloud droplet concentration as representative values. Here, geometric center is not necessarily always correspond to the

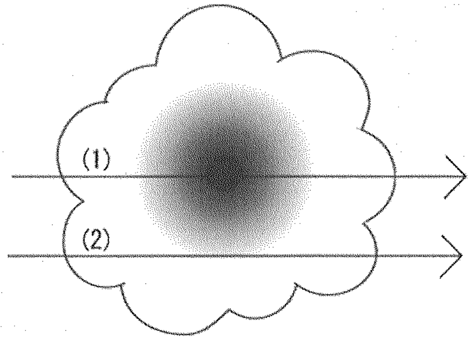

Fig. 3. Conceptional figure of horizontal section of cloud.

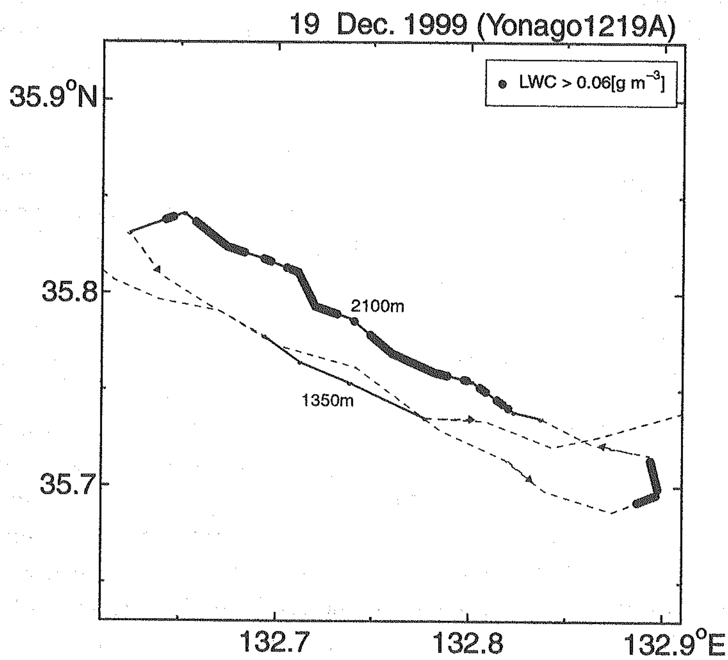

Fig. 4. Magnified flight courses: December 19, 1999 (Yonago 1219A).

position with maximum value. It is for this reason that this phenomenon may be explained by non-uniform entrainment. In these cases, maximum values were also adopted as representative value.

Figure 4, which depicts the flight on December 19, 1999 (Yonago 1219A),

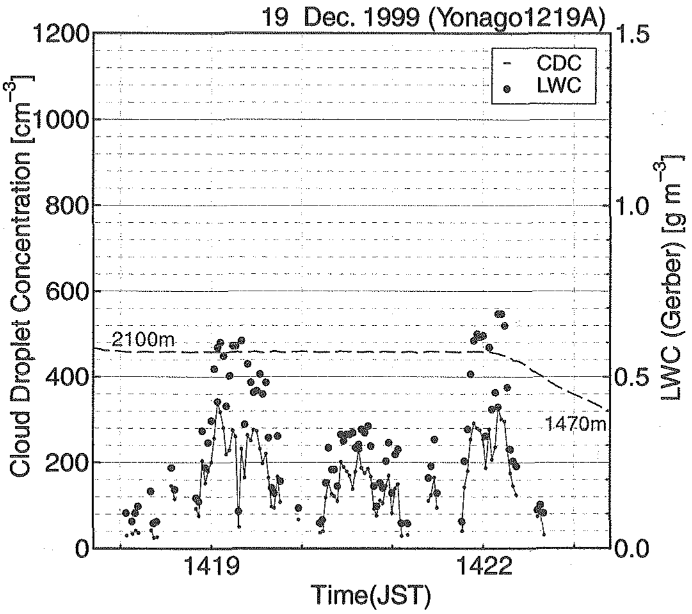

Fig. 5. Spatial distribution of cloud droplet concentration and liquid water content described by time for December 19, 1999 (Yonago 1219A). This figure shows the values in the division represented by the thick solid line in Fig. 4.

shows the positions where the aerosols and cloud droplets were observed. The magnified flight course is described by connecting the positions corresponding to every 30 sec. The big shaded areas represent the positions detecting cloud droplet. The thick solid line indicated by 1,350 m is the division due to the horizontal flight. An aerosol concentration of more than 0.3 μm in diameter was constant in this division, so we adopted the mean value of these as the aerosol concentrations under the cloud base.

The thick solid line indicated by 2,100 m in Fig. 4 is the division formed by the penetrating flight. The spatial distribution of the cloud droplet concentration and liquid water content in the division is represented in Fig. 5. It is seen that the three patterns have a large value in the central portion and small values at both edges. This characteristic corresponds to that explained in Fig. 3. We believed from this characteristic that this flight penetrated three clouds. We also confirmed this fact from the pictures taken by the CCD camera. The representative values of cloud droplet concentration are shown by the large dot on each solid line.

Figure 6 shows the spatial distribution of the cloud droplet concentration

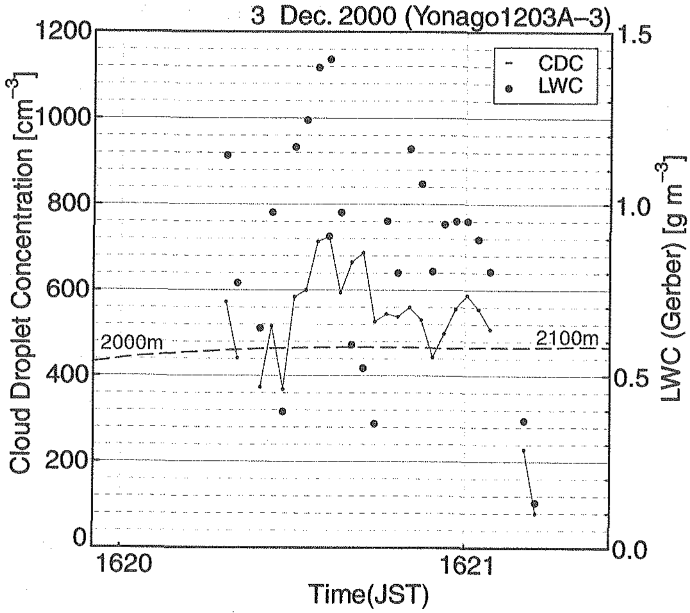

Fig. 6. As in Fig. 5 except for December 3, 2000 (Yonago 1203A-3).

and liquid water content for the flight on December 3, 2000 (Yonago 1203A-3). It can be seen in Fig. 6 that the cloud droplet concentration and liquid water content have a maximum value in the center of the cloud and small values at both edges. We specified the value shown by the large dot on the solid line in Fig. 6 as representative value. An aerosol concentration more than 0.3 μm in diameter was constant in this division where the aircraft flew at a constant level, so the mean value in this division was adopted as the representative value of the aerosol concentration.

Figure 7 shows the spatial distribution of cloud droplet concentration and liquid water content on December 5, 2000 (Yonago 1205A-2). The flight course shows that the aircraft penetrated the same cloud twice during its circular flight. Therefore, we can compare with the cloud droplet concentration and liquid water content at two different locations on the same horizontal flight in the same cloud. The cloud droplets observed at 1536 : 45-1537 : 00 JST and 1537 : 20-1537 : 40 JST are termed X and Y, respectively. Both cases showed similar pattern : a large value in the central position and small values at both edges for the cloud droplet concentration and liquid water content. But, the X concentration was 531 cm^{-3} and the Y concentration was 647 cm^{-3}. This shows that

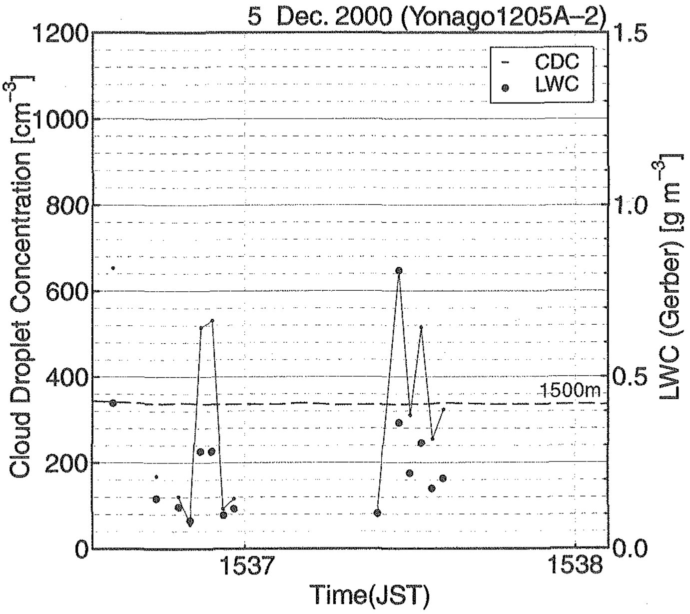

Fig. 7. As in Fig. 5 except for December 5, 2000 (Yonago 1205A-2).

there is a different in cloud droplet concentration even on the same horizontal flight in the same cloud. This fact is consistent with the conceptional figure shown in Fig. 3. It is believed that this fact is caused by entrainment. In this case, X was affected by entrainment much more than Y. Therefore, we chose Y as representative values.

So far, we have shown nearly homogeneous mixing cases. But, there is one case in which the actual distributions of the cloud droplet concentration and liquid water content are not similar to the conceptional figure shown in Fig. 3. Such a case is shown as follows. Figure 8 shows the spatial distribution of cloud droplet concentration and liquid water content on December 3, 2000 (Yonago 1203A-2). In this case, observation of the aerosol concentration was carried out near position where the cloud droplet was observed. It is seen from flight course that three clouds were positioned one behind the other. It is confirmed from Fig. 8 that the distributions of the cloud droplet concentration and liquid water content are not always symmetrical. It is thought that the aircraft flew by the edge region of cloud. We adopted each large dot on the solid lines as representative values.

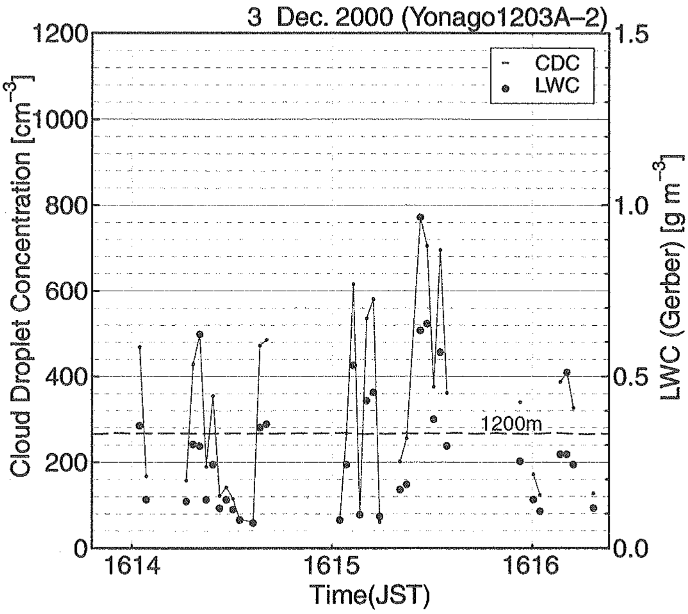

Fig. 8. As in Fig. 5 except for December 3, 2000 (Yonago 1203A-2).

3.3 Vertical structure of cloud represented by cloud droplet concentration and liquid water content

Generally speaking, supersaturation reaches a maximum near position above the cloud base and decreases with the increase of height. Cloud droplets are formed above the cloud base and their concentrations are determined by the maximum supersaturation near the cloud base. A portion of the cloud droplets may possibly evaporate by entrainment and mixing during the rise of air parcel with the cloud droplet. In the center region, represented by the shaded area in Fig. 9, it is thought that the updraft is strong and entrainment is weak. Therefore, the liquid water content in the region is thought to be nearly adiabatic. The region keeps the maximum cloud droplet concentration formed near the cloud base. If air parcel rises in the center of the cloud, the cloud droplet concentration at each height is expected to be equal to the concentration formed near the cloud base.

If the aircraft penetrates a cloud at several heights or the aircraft penetrates a cloud by ascending and descending flights, we can describe the vertical distribution of the cloud droplet concentration and liquid water content. Such

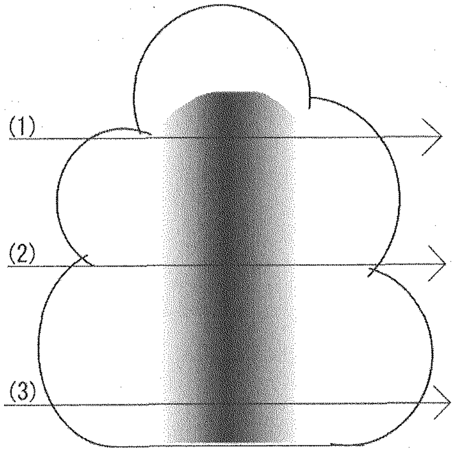

Fig. 9. Conceptional figure of vertical section of cloud.

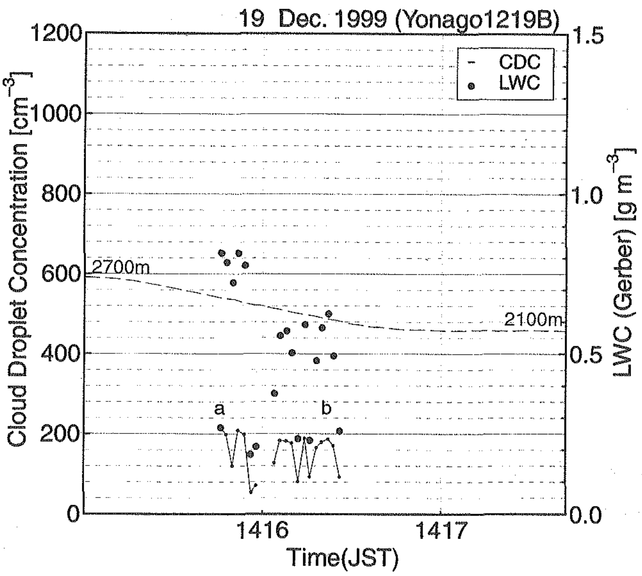

Fig. 10. As in Fig. 5 except for December 19, 1999 (Yonago 1219B).

a case is shown and the vertical structure is characterized as follows.

Figure 10 shows the spatial distribution of cloud droplet concentration and liquid water content on December 19, 1999 (Yonago 1219B). In this case, the observation was carried out during the flight descent. We can see the vertical

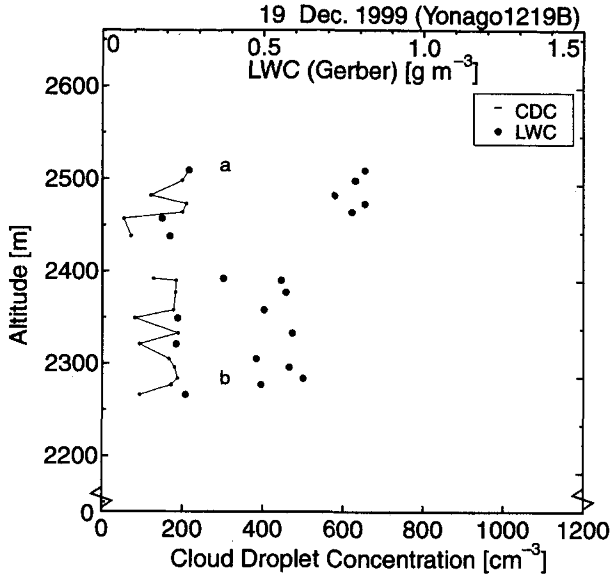

Fig. 11. Vertical distribution of cloud droplet concentration and liquid water content for December 19, 1999 (Yonago 1219B). a and b correspond to a and b in Fig. 10, respectively.

distribution of the cloud droplet concentration and liquid water content (Fig. 11) ; *a and* b *in Fig. 11 correspond to* a *and* b *in Fig. 10, respectively.* It is seen in Fig. 11 that the cloud droplet concentration shows nearly equal value despite the height, and liquid water content increases with increasing height. This shows that the cloud droplets continue to grow, keeping an equal concentration as they rise. This case is consistent with that explained in Fig. 9. Therefore, this case is not thought to be affected much by entrainment. Because the cloud droplet concentration has a maximum value at a in this cloud, this value was regarded as the representative value.

For December 3, 2000 (Yonago 1203A-1), the observation was carried out during the circular flight ascent, so we can see the vertical distribution of the cloud droplet concentration and liquid water content (Fig. 12). From the flight course, it appears that the aircraft penetrated the same cloud twice. This is also explained by the fact that the cloud droplets were not detected at 1,050-1,130 m in height. It is seen in Fig. 12 that the cloud droplet concentration and liquid water content have a maximum value at about 950 m in height and decrease with increasing height. They increase again with increasing height from the height of 1,150 m and have a maximum value at about 1,220 m in

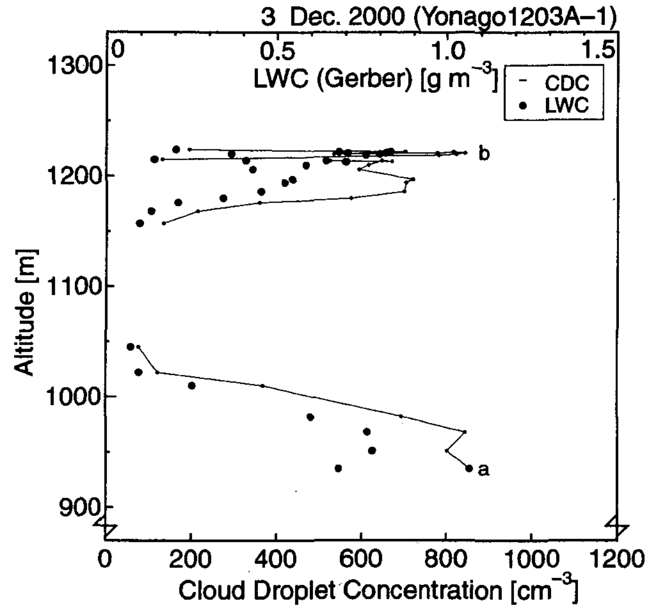

Fig. 12. As in Fig. 11 except for December 3, 2000 (Yonago 1203A-1).

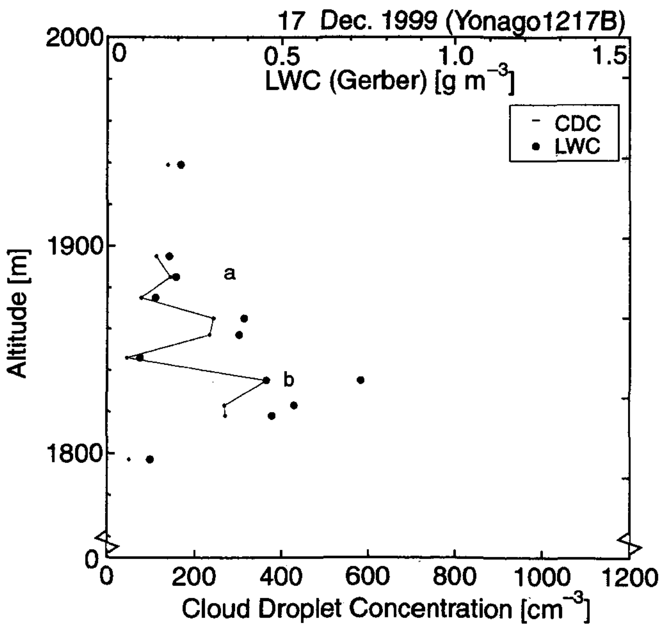

Fig. 13. As in Fig. 11 except for December 17, 1999 (Yonago 1217B).

height. Concentrations become nearly equal at 950 m and 1,220 m in height despite the different heights. It is expected from this fact that the concentrations at each height are nearly equal to those of flights penetrating clouds through their center.

For December 17, 1999 (Yonago 1217B), the observation was carried out during the flight descent, so we can see the vertical distribution of the cloud droplet concentration and liquid water content (Fig. 13). It is seen from Fig. 13 that both the cloud droplet concentration and liquid water content decrease with increasing height. In this case, because the height of the cloud top was reported to be 1,900 m by the copilot, it is considered that we observed the portion evaporating by entrainment.

4. Discussion

4.1 Calculation of adiabatic liquid water content

If air parcel rises, keeping the adiabatic process, the cloud droplets formed at the cloud base remain equal in concentration and increase in liquid water content. But, actual cloud droplets change in size and concentration by mixing and entrainment, and so the liquid water content does not always increase with the increase in height. Therefore, many methods have been tried to extract data that are not affected by entrainment. For example, Leaitch et al. (1996) classified data according to the range of the standard deviation in the updraft. Vong and Covert (1998) classified data according to high or low liquid water contents. Lawson and Blyth (1999) defined the adiabatic core, which is narrow in the width of the cloud droplet size distribution and shows a maximum value in updraft speed. They adapted the data in the adiabatic core. In order to estimate the deviation from the adiabatic process, we calculated the adiabatic liquid water content by assuming that the air parcel rises adiabatically from cloud base to the observation height, and compared the observed value with the calculation value. Then, we adopted the height of cloud base reported by the copilot and performed the abovementioned calculation. We calculated the liquid water content at the observation height, adding the each liquid water content of every 100 m in depth, as estimated by the moist adiabatic lapse rate from the cloud base to the observation height.

4.2 Relationship between aerosol concentration and cloud droplet concentration

Figure 14 shows the comparison of the observation values with the calcu-

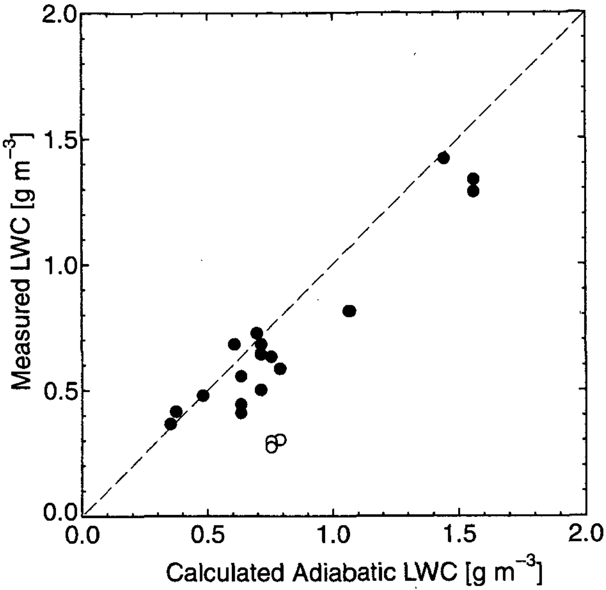

Fig. 14. Comparison of observed values with calculated values at observation height.

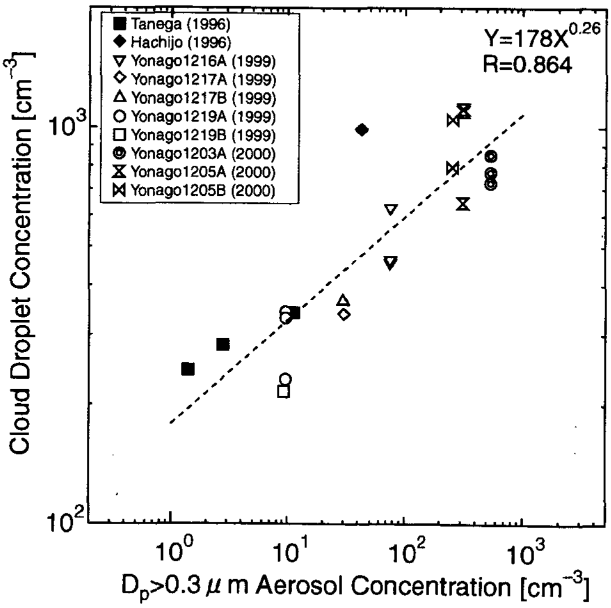

Fig. 15. Relationship between aerosol concentration and cloud droplet concentration.

lated values of the adiabatic liquid water content at the observation height. Three points, indicated by open circles, are fairly smaller than adiabatic liquid water content, so we regarded these three points as non-adiabatic liquid water content and excluded them. There are some data in which the observed values are somewhat larger than the adiabatic values ; this may be due to the disagreement between the actual cloud base and observation. Hereafter, we use the data of the 17 points mentioned above, and the 4 points obtained by aircraft observation at the Tane Island and the Hachijyo Island in order to discuss.

Figure 15 shows the relationship between the aerosol concentration and cloud droplet concentration. It is seen in Fig. 15 that the cloud droplet concentration has a tendency to increase with increasing aerosol concentration. The dotted line indicates a regression line to all data, with the correlation coefficient of 0.864. It is seen from the regression formula that the rate of increase of the cloud droplet concentration becomes less steep in large aerosol concentrations than in small aerosol concentrations. Here, it is seen that the cloud droplet concentration is larger than the aerosol concentration, because it is thought that even the aerosols less than 0.3 μm in diameter are activated and form cloud droplets in observed clouds.

5. Conclusions

Aircraft observations were carried out off the Oki Islands during the periods of December 1999 and December 2000. We analyzed about five day's worth of data containing aerosol concentration and cloud droplet concentration.

In order to closely examine the relationship between the aerosol concentration under a cloud base and the cloud droplet concentration in the same cloud, we selected clouds without precipitation and obtained the aerosol concentration data during horizontal flights under the cloud base. It is thought that the cloud droplet concentration decreases due to the collection by rain drops, and aerosol concentration changes with height. We selected twenty cases satisfying these standards, and represented the horizontal and vertical structures of clouds by cloud droplet concentration and liquid water content. During horizontal penetrating flights, we measured the maximum values in the cloud droplet concentration and liquid water content at the center portion of the cloud. During ascending and descending flights, we observed that cloud droplet concentration shows nearly equal value despite the change in height, and the liquid water content increases with increasing height. These results reflect the fact that cloud droplets are formed at the cloud base and grow with the increase in height, maintaining the same concentration. Therefore, penetration exactly at the center portion of a cloud was confirmed to be important.

We selected further data which are close to the adiabatic liquid water content. As a result, it was seen that the cloud droplet concentration has a tendency to increase with increasing aerosol concentration. The relationship was represented by the regression formula $Y=178X^{0.26}$ with 0.864 as the correlation coefficient. It was also confirmed that the rate of increase of the cloud droplet concentration in large aerosol concentrations is less steep than in small aerosol concentrations.

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