Structure and Reflectance of Winter Maritime Stratocumulus Clouds

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Abstract

To obtain the relationship between the structure and reflectance of winter maritime stratocumulus cloud tops, observations using an aerial stereophotographic method were carried out from January 1989 to January 1991 in the area off Wakasa Bay in the Japan Sea, and around the Amami Islands in the Pacific Ocean. The relationship between cloud top heights and the reflectance of the cloud was first investigated, and a positive correlation was found to exist. An especially high correlation was obtained for the clouds over the Amami Island data. Next, the relationship between the cloud area ratio and the reflectance of the cloud top surface was examined. Results indicated that in areas of low reflectance, the cloud top heights were relatively low and widely distributed. The cloud tops were sharp and jagged in shape. In contrast, in areas of high reflectance, high cloud top heights were found, being uniform on the average. Their shapes were flat and trapezoidal in comparison with the jagged nature of the other clouds.

For the clouds north of the Amami Islands, the cloud top heights were lower than those found in other cases. The difference between the maximum and minimum cloud top heights was more than 400 m and the values of reflectance were greater than those in the other observations. The difference in the reflectance of the clouds over the Amami Islands may result from the difference between the liquid-water paths.

1. Introduction

The shape, structure, and roughness of clouds have a significant influence upon solar and atmospheric radiation. In particular, clouds such as widespread stratocumulus clouds over the oceans can affect the climate through the coupling of radiative, microphysical, and convective processes. To date, there have been no observational results concerning the fine structure of the cloud top roughness of

stratocumulus clouds. Observations made using stereophotographs taken from the ground, aircraft, and polar orbiting satellites have focused on the external changes in the shape of clouds rather than structural changes. Magono *et al.* (1967a) observed the three-dimensional configuration of cirrus clouds by employing the stereoscopic photograph method from the ground. Furthermore, Magono *et al.* (1967b, c) analyzed the distribution of the three-dimensional configuration of cirrus clouds and the cross section of a cold front using stereoscopic photographs. These photographs were taken by a 16 mm time-lapse movie camera mounted within an

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(a)

(b)

Fig. 1. Photograph of the observation aircraft
(a) schematic illustration of the installed
observational equipments (b).

aircraft on a return trip from Tokyo to Los Angeles. Hasler and others carried out three-dimensional stereoscopic analyses of clouds and the air flow patterns around hurricanes and thunderstorms using a geostationary meteorological satellite (Hasler, 1981; Mack *et al.*, 1983; Hasler and Morris, 1986). Recently, Kikuchi *et al.* (1991) analyzed the unevenness of the cloud base structure of stratocumulus clouds using a stereophotographic method in which two wide-angle lens cameras having a 28 mm focal length were mounted on two separate theodolites. The optical axes of these cameras were pointed in the vertical direction. These cloud observations, however, were not concerned with the relationship between the roughness and radiative properties of the cloud top surface.

To obtain the relationship between roughness and radiative properties, in situ observations using a stereo aerial photographic method to determine the roughness of the cloud top surface were carried out from January 1989 to January 1991 from the Nagoya and Amami airports. The present research is part of the programme of the Cloud-Radiation Experiment of the World Climate Research Programme (WCRP) in Japan. In this paper, the results of the comparison among the roughness of cloud top surfaces, reflectance, and the liquid water path of winter maritime stratocumulus clouds will be discussed.

2. Observations

The Cessna 404 (Titan) used for this project is shown in Fig. 1a. The arrangement of the camera,

(a)

(b)

Fig. 2. Photographs of the motor-driven and microvideo cameras fixed pointing downward on the floor of the aircraft fuselage (a) and lenses of them (b).

Fig. 3. Surface weather chart at 0900 JST November 11, 1990.

Fig. 4. Map showing the general location of the Wakasa Bay observational area (left) and an enlarged map of the area indicated by the boxed region (right).

pyranometers and microwave radiometer on the aircraft is schematically shown in Fig. 1b. The arrangements of 35 mm motor-driven cameras of 28 mm focal length and microvideo cameras are as follows;

a set of the motor-driven camera and microvideo camera is fixed, pointing downward, on the central part of the bottom of the fuselage, as shown in Fig. 2a and 2b. A similar set of the motor-driven cam-

(a)

(b)

Fig. 5. Photographs of the cloud top surface of the Wakasa Bay Sc of an oblique view (a) and that taken by the down ward pointing motor-driven camera (b).

era and video camera is mounted, pointing at an oblique angle on the frame along the inside wall of the fuselage. For the analysis of the cloud top surface structure, the downward pointing motor-driven camera was used while the oblique camera and video cameras were employed to obtain a general view of the target clouds. The observation flights were conducted to observe stratocumulus clouds over the ocean during the winter season. This paper will examine three cases; November 11, 1990 off shore of Wakasa Bay in the Japan Sea, and January 14 and 18, 1991 in areas off shore to the east and north of the Amami Islands, respectively, in the Pacific Ocean.

3. Results of analysis

3.1 Clouds off Wakasa Bay

Figure 3 represents the surface weather chart for 0900 JST November 11, 1990 of the area around the Japan Islands. As seen in the weather chart, the Japan Islands are under the influence of a high pressure to the south and a low pressure to the north pattern with the observational area under prevailing westerly winds. Figure 4 shows the location of the observational area. The aerial stereophotographic observations were carried out from 1129 to 1249 JST on November 11, 1990. Throughout the observational period, the flight altitude was maintained at 2850 m, where the wind direction and velocity were 296° and 20 ms^{-1} , respectively. The time interval between stereophotographs was 2 seconds

Fig. 6. Horizontal distributions of cloud top heights (indicated by the color-graded legend) and reflectance along the 8 km flight path of the Wakasa Bay during November 11, 1990.

Fig. 21. Horizontal distributions of cloud top heights (indicated by the color-graded legend) and reflectance along the flight path over the area north of the Amami Islands during January 18, 1991.

Fig. 14. Horizontal distributions of cloud top heights (indicated by the color-graded legend to the right of the middle panel) and reflectance along the flight path over the area east of the Amami Islands during January 14, 1991. The distributions are for distances along the flight path of 0.0 to 5.0 km (upper), 5.0 to 10.0 km (middle), and 10.0 to 15.0 km (bottom).

Fig. 7. Distribution of average cloud top height and reflectance of the Wakasa Bay Sc as shown in Fig. 6.

during this flight. A sample photograph taken by a hand-held camera through the aircraft window is shown in Fig. 5a. As seen in the figure, the cloud top surface is not smooth; a relatively large rough surface appears. An analysis was conducted on the data from 1243:20 to 1245:10 JST along the flight path. Figure 5b shows an example of the top surface of the target cloud photographed by aiming the camera directly downward at 1244:00 JST. Comparing Fig. 5a with Fig. 5b, a large difference can be seen in the images of the cloud top surfaces.

Figure 6 represents the results of the analysis over the 8 km length of the flight path and covering 0.4 km on each side (0.8 km in total width) of the flight path. Cloud top heights in this example are calculated for every 60 m. The accuracy of the analysis using an image analyzer is approximately 1.5% in height. Color grades corresponding to the cloud top heights are shown in the lower right-hand corner of the figure, ranging from greater than 1940 m to greater than 2360 m. For this case, the maximum and the minimum cloud tops were 2370 m (located at a distance of 5.390 km and -0.190 km) and 1881 m (1.730 km and -0.400 km), respectively. The height of the cloud base for this example was 900 m above sea level, estimated from the sounding data at Yonago.

The lower curve in Fig. 7 shows the average cloud height over an $0.8 \text{ km} \times 1.0 \text{ km}$ area represented by 1.0 km running mean for each 0.5 km along the flight path. The upper curve in the figure is the ratio of the outgoing radiative flux ($F_{\uparrow}$) to the incoming total radiative flux ($F_{\downarrow}$) (hereafter termed reflectance) as a function of distance along the flight path. The curves appear to be correlated to each other except for observations at distance from 6.0 to 7.5 km. The correlation coefficient between reflectances and cloud top heights as presented in Fig. 8 was determined to be 0.593. As seen in this figure, the data are scattered, especially between reflectance values of 0.60 and 0.65 and between cloud top heights 2200 m and 2300 m. It is concluded that the relatively

Fig. 8. Correlation between the average cloud top heights and reflectance of the Wakasa Bay Sc shown in Fig. 6.

low correlation coefficient is the result of this scatter. Aside from the unreasonable scatter between the reflectance values of 0.60 and 0.65, there is a good correlation.

Returning to Fig. 6, a comparison is made of the relationship between the cloud areas having heights greater than the threshold values of 1940 to 2420 m at 60 m each to the total cloud area at the 1940 m height (hereafter referred to as the cloud area ratio). For this purpose, cloud areas at distance from 1.0 to 2.0 km along the flight path are selected as representative of a typical rough area while those at distance of 3.0 to 4.0 km as representative of a relatively flat area. The results for both areas are shown in Fig. 9. As clearly illustrated, the cloud area ratio curves show distinct shapes. For the cloud area at distances between 1.0 and 2.0 km, the decrease of cloud heights to total cloud area is sharp, as shown in the left-hand panel, compared to that in the right-hand panel for areas at distance of 3.0 to 4.0 km. From this result, it can be seen that the cloud top heights are widely distributed over the range from 1900 to 2240 m, with the reflectance being 0.58. In contrast, the cloud top heights are relatively uniform, from 2200 to 2300 m as shown in the right-hand panel, having a reflectance of 0.77.

Figure 10a represents the distribution of cloud top heights for the entire analyzed area along the flight path from 0 to 8.0 km. Consequently, the number density of cloud top size in each cloud height threshold, namely above 2200, 2250, and 2300 m. In this calculation, cloud areas above each threshold height are assumed as having a circular shape. Figure 10b represents the relationship between the number density and the radius of the cloud areas above each threshold height. In this figure, solid circles connected solid line, triangles connected dashed line, and squares connected dash-dotted line represent the relationship for each threshold height at 2200, 2250, and 2300 m, respectively. For this observed

Fig. 9. Curves of cloud area ratio at distances along the Wakasa Bay flight path of (a) 1.0 to 2.0 km, and (b) 3.0 to 4.0 km. Reflectance values over (a) and (b) are 0.58 and 0.77, respectively.

Fig. 10. Cloud top heights as a function of cloud area ratio (a) and the number density of cloud top size (b) as a function of equivalent cloud radius over the analyzed area of the 0 to 8 km Wakasa Bay flight path.

data set, the total number of cloud areas above each cloud height threshold differ; 14.4 at 2200 m, 17.1 at 2250 m, and 8.3 km⁻² at 2300 m. The relationship between the number density and the radius is, however, similar.

3.2 Clouds east of the Amami Islands

Figure 11 represents the surface weather chart at 0900 JST January 14, 1991 around the Japan Islands. As seen in the weather chart, the Japan Islands are under a weak winter monsoon pressure pattern with weak prevailing westerly or northwesterly winds over the observational area. Figure 12 shows the location of this observational area east the Amami Islands. The aerial stereophotographic observations were conducted from 1137 to 1242 JST on January 14, 1991. Flight altitudes were maintained at 3150 m over the first half and 5100 m over the latter half of the observational period. Following the increase in flight altitudes, the time interval

between stereophotographs over the first and latter halves was changed from one frame per 2 seconds to one per 5 seconds. A sample of oblique photograph of the stratocumulus cloud taken by a hand-held camera through the aircraft window is shown in Fig. 13a, while 13b is that of a target cloud photographed by the downward-pointing camera at 1143:46 JST. An analysis was performed on the data collected for 1143:00 to 1145:58 JST along the flight path.

Figure 14 represents the analyzed results over the 15 km length and 1 km width along the flight path. The northern direction relative to the width is indicated by the arrow in upper right of the figure. The average wind direction and velocity during the flight were 278° and 9.0 ms⁻¹ respectively. Cloud top heights in this case were calculated over each 60 m. Color grades corresponding to the cloud top heights are shown to the right of the middle panel of the figure, with values ranging from greater than

Fig. 11. Surface weather chart at 0900 JST January 14, 1991.

Fig. 12. The same as in Fig. 4 except for the observational area east of the Amami Islands.

(a)

(b)

Fig. 13. The same as in Fig. 5 except for the area east of the Amami Islands.

1940 m to greater than 2360 m. From the horizontal distributions of cloud top heights, areas of relatively higher heights are recognized at distance around 4.5 to 5.5, 9.0 to 10.0, 11.5 to 12.5, and 14.0 to 15.0 km. In contrast, areas of relatively lower heights are found at distance of around 0 to 1.5 and 7.0 to 8.0 km. The maximum cloud top height of 2420 m is found at a distance of around 12 km, while the minimum of 1950 m occurs near 1.5 km. In this observation, the difference between the maximum and minimum heights is 470 m. The upper curve in each cloud top height panel shows the reflectance which corresponds to the cloud top height distributions. The reflectance and cloud height distribution appear to have a good correspondence between them. The upper curve in each panel of Fig. 15 represents the reflectance as shown in Fig. 14; the lower curves are the average cloud heights over an area of 1.0

km $\times$ 1.0 km, represented by a 1.0 km running mean at each 0.5 km distance increments along the flight path. The correlation coefficient between these two distributions as presented in Fig. 16 was determined as 0.772. Since a good correlation was obtained, the relationship between the average reflectance and the cloud area ratio was examined. The cloud areas selected for analysis were between distance of 0.5 and 1.5 km along the flight path as shown in Fig. 17a, 5.5 and 6.5 km as in 17b, 8.5 and 9.5 km as in 17c, and 13.5 and 14.5 km as in 17d. The average reflectance over each cloud area is 0.47 for Fig. 17a, 0.51 for 17b, 0.70 for 17c, and 0.73 for 17d. As can be determined from the figure, the cloud area ratio curves show characteristic features which are dependent on the reflectance. For instance, the curve representing cloud height to cloud area ratio in Fig. 17a shows an abrupt decrease from 2300 m to 1900 m. In contrast,

Fig. 15. Distribution of average cloud top heights and reflectance of the Amami Islands Sc as shown in Fig. 14.

Fig. 16. Correlation between the average cloud top heights and reflectance of the Amami Islands Sc as shown in Fig. 14.

Fig. 17. Curves of cloud area ratio at distances along the flight path east of the Amami Islands of (a) 0.5 to 1.5 km, (b) 5.5 to 6.5 km, (c) 8.5 to 9.5 km, and (d) 13.5 to 14.5 km. Average reflectance values over (a), (b), (c), and (d) are 0.47, 0.51, 0.70, and 0.73, respectively.

Fig. 18. Cloud top heights as a function of cloud area ratio (a), (c), and (e), and corresponding number densities of cloud top size versus cloud radius (b), (d), and (f) for each analyzed area along the flight path east of the Amami Islands at distances of 0.0 to 5.0, 5.0 to 10.0, and 10.0 to 15.0 km, respectively. The solid circles connected solid lines, solid triangles connected dashed lines, and solid squares connected dash-dotted lines represents the number densities for the various heights shown below each figure.

Fig. 19. The same as in Fig. 4 except for the observational area north of the Amami Islands.

the curves shown in 17b, 17c, and 17d appear to show little changed, regardless of the differences in their reflectance. However, the cloud heights in the overall selected target areas differed from each other. In particular, the respective slopes of the linear portion of curves 17b and 17d were similar, -1.29×10^2 and -1.28×10^2 ; however, the respective values of reflectance were 0.51 and 0.73. It is reasonable to consider that the difference in cloud heights corresponds to the cloud thickness, since the cloud base height was determined by the small restricted observational area for the cases of stratocumulus clouds over the ocean. It is concluded, therefore, that the difference in the values of reflectance depends on the cloud top height, namely, the cloud thickness.

Figure 18 displays the cloud area ratio curves in the left hand panels and the corresponding number density distributions of cloud top sizes (equivalent circular area) as a function of radius above each threshold cloud height on the right. The cloud area ratio curves shown in Fig. 18a, 18c, and 18e correspond to the areas analyzed along the flight path at distances of 0 to 5, 5 to 10, and 10 to 15 km, respectively. The size distributions are for values greater than 2200, 2250, and 2300 m in 18b and 18d, and greater than 2300, 2350, and 2400 m in 18f. The solid circles connected solid lines, triangles connected dashed lines, and squares connected dashed-dotted lines represent each threshold height as shown in the legend in the lower right of each panel. The number density of clouds above each threshold height decreases systematically as shown

in Fig. 18b and 18f. In these cases, the gradients of the regression lines are similar for each threshold height. In contrast, the number density of clouds above each threshold height is equivalent and the gradients of the regression lines are similar as shown in Fig. 18d. This can be explained by noting that the total number of clouds per km^2 is approximately the same.

3.3 Clouds north of the Amami Islands

The third observed data set gathered on Jan. 18, 1991 over an area governed by high pressure pattern centered in the northeast district of the People's Republic of China with a weak northerly wind prevailing over the observational area. Figure 19 represents the location of the observational area to the north of the Amami Islands. Figure 20a and 20b displays photographs of an oblique and downward views, respectively, of the cloud top surface of stratocumulus clouds over the ocean.

Figure 21 represents the horizontal distributions of cloud top heights separating 40 m each and the reflectance along the 10 km length and 1 km width of the flight path. In comparison with the previous examples, these cloud top heights are relatively lower and there is a smaller variation in the values of reflectance. Here, the correlation coefficient is larger than that found in the previous examples, calculated as 0.816 and shown in Fig. 22. In a similar manner to the previous examples, the cloud areas at flight path distances between 9.0 and 10.0 km were selected to represent typical lower cloud heights and

(a)

(b)

Fig. 20. The same as in Fig. 5 except for the area north of the Amami Islands.

Fig. 22. Correlation between the average cloud top heights and reflectance of the clouds over the area north of the Amami Islands, as shown in Fig. 21.

between 1.0 and 2.0 km for relatively higher cloud heights as shown in Fig. 23a and 23b, respectively. The values of reflectance for these cloud areas were 0.68 and 0.84 for Fig. 23a and 23b, respectively. The cloud area ratio curves can be distinguished according to their different values of reflectance as shown in Fig. 23. The reflectance value of 0.84 was the largest among the analyzed cases. However, the cloud top heights which correspond to the cloud thicknesses were lower than those in the other cases. In addition, the cloud area ratio curve as shown in Fig. 23a is distinctive compared with other cases, and the difference between the maximum and minimum cloud top heights was more than 400 m.

3.4 Relationship between liquid water path and cloud top height

Information concerning the liquid water path of the target clouds was obtained by use of a microwave

Fig. 23. Cloud area ratio curves at distances along the flight path north of the Amami Islands of (a) 9.0 to 10.0 km, and (b) 1.0 to 2.0 km. Average reflectance values over (a) and (b) are 0.68 and 0.84, respectively.

Fig. 24. Correlation between the average cloud top height and the liquid water path along the flight path over the area east of the Amami Islands during January 14, 1991.

radiometer (Fig. 1b) during the observational periods. To date, the measurement of liquid water path using an airborne microwave radiometer such as used in this system has not been well established. For this reason, the liquid water path was compared to the cloud top height, which corresponds to the cloud thickness of maritime stratocumulus clouds, since the height of the cloud base described above is considered to be relatively constant.

The second set of observation east of the Amami Islands along the 15 km flight path are first examined. Figure 24 shows the correlation between the liquid water paths and cloud top heights, with a calculated correlation coefficient of approximately 0.7. In these results, the values of liquid water paths are scattered from 5 to 20 mgcm^{-2} , and the cloud top

Fig. 25. The same as Fig. 24 except for the flight path over the area north of the Amami Islands during January 18, 1991.

heights range from 2100 to 2300 m. In contrast, the results for the third observational set over the area of the Amami Islands along the 10 km along the flight path are exhibited in Fig. 25. Here, the correlation coefficient is 0.85, being larger than the previous case. The values of liquid water paths are scattered from 17 to 34 mgcm^{-2} and are considerably larger, although the cloud top heights are somewhat lower than the previous case; from 1470 m to 1575 m. It is possible that the differences between the reflectance values in the previous case (0.47 to 0.73) and this case (0.68 to 0.84) result from differences in the liquid water paths; 5 to 20 mgcm^{-2} previously and 17 to 34 mgcm^{-2} here.

4. Concluding remarks

To obtain the relationship between the roughness or unevenness and reflectance of cloud top surfaces

of winter maritime stratocumulus clouds, observations using an aerial stereophotographic technique were carried out from January 1989 to January 1991 off Wakasa Bay in the Japan Sea, and over regions east and north of the Amami Islands in the Pacific Ocean.

The relationship between cloud top height and the reflectance of stratocumulus clouds was first investigated. A positive correlation was found between them, with the values of the correlation coefficient being 0.593 for the Wakasa Bay observation, and 0.772 and 0.816 for the those east and north of the Amami Islands, respectively. An especially high correlation was found in the data from the Amami Islands. It was concluded therefore that the cloud top height, equivalent to the cloud thickness in the case of stratocumulus clouds over the ocean, was the primary factor for differences in the reflectance of stratocumulus clouds.

Second, the relationship between the cloud area ratio and the reflectance of the cloud top surface was examined. It was found that in low reflectance areas, the cloud top heights were relatively low and widely distributed. In addition, the cloud tops were sharp and jagged in appearance. In contrast, high reflectance areas were found to have high and uniform cloud top heights on the average, with shapes that were flat and trapezoidal in appearance.

Finally, calculations were made to obtain the number density per unit area of cloud top size (equivalent in area to circular shaped clouds) found at heights greater than each threshold cloud height as a function of cloud radius. Results showed that a large height difference and large scale roughness existed in the low reflectance areas, while small height differences and small scale roughness of cloud top heights were found in high reflectance areas. For the area north of the Amami Islands, however, the reflectance values were greater than the other observations. However, the cloud top heights were lower than those found in the other cases, while the differ-

ence between the maximum and minimum cloud top heights was more than 400 m. It was concluded that the difference in the values of reflectance for these Amami observations may be due to difference found in the liquid water path along the flight paths.

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References

- Hasler, A.F., 1981: Stereoscopic observations from geosynchronous satellites: An important new tool for the atmospheric sciences. *Bull. Amer. Meteor. Soc.*, **62**, 194–212.
- Hasler, A.F. and K.R. Morris, 1986: Hurricane structure and wind fields from stereoscopic and infrared satellite observations and radar data. *J. Clim. Appl. Meteor.*, **25**, 709–727.
- Kikuchi, K., M. Fujii, R. Shirooka and S. Yoshida, 1991: The cloud base structure of stratocumulus clouds. *J. Meteor. Soc. Japan*, **69**, 701–708.
- Mack, R.A., A.F. Hasler and R.F. Adler, 1983: Thunderstorm cloud top observations using satellite stereoscopy. *Mon. Wea. Rev.*, **111**, 1949–1964.
- Magono, C., T. Harimaya and T. Yagi, 1967a: Observation of cirrus cloud by trigonometric method. *Geophys. Bull. Hokkaido Univ.*, **18**, 83–98 (in Japanese with English abstract).
- Magono, C., K. Kikuchi and M. Kajikawa, 1967b: Distribution of low-level cloud rows and three dimensional analysis of cirrus clouds, —Cloud over the Pacific Ocean: Part-2. *J. Meteor. Soc. Japan*, **45**, 467–477.
- Magono, C., K. Kikuchi and T. Kasai, 1967c: Cloud distribution across a cold front over the middle northern Pacific Ocean, —Clouds over the Pacific Ocean: Part-3. *J. Meteor. Soc. Japan*, **45**, 478–489.

冬季の海上の層積雲の構造と反射率

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冬季の海上の層積雲の雲頂の構造と反射率の関係を調べるために、航空機によるステレオ写真観測法を使った観測が1989年1月から1991年1月にわたって、日本海の若狭湾沖および奄美諸島周辺の太平洋上で行われた。

最初に、雲頂高度と反射率との間の関係が調べられ、両者の間にはかなりよい相関が認められた。特に奄美諸島周辺での観測では高い相関が認められた。次に Cloud area ratio (雲の領域率) と雲頂の反射率との関係が調べられた。その結果、低い反射率の雲域では雲頂高度が比較的低くて雲層が薄く、また、その高度差は大きく、雲頂の形状は鋸の歯のように鋭かった。一方、高い反射率の雲域では雲頂高度が高くて雲層が厚く、そして一様で形状は平で台形のような形をしていた。

しかし、奄美諸島北部の例では、雲頂高度が他の2例に比して低く、しかも最高雲頂高度と最低雲頂高度との高度差が400m以上もある層積雲であったにもかかわらず、その反射率は比較的高かった。この反射率の違いは liquid water path の差によるものと推定される。

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