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Roughness of Cloud Top Surfaces of Winter Stratocumulus Clouds over the Ocean
—— Preliminary Investigations on Cloud and Radiation ——

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Abstract

To investigate the contribution of the roughness or unevenness of cloud top surfaces upon solar radiation, the cloud top heights of the stratocumulus clouds over the ocean were measured by means of the stereophotographic method using an aircraft over Wakasa Bay in the Japan Sea and around Amami Islands in the Pacific Ocean during the winter monsoon seasons of 1989, 1990 and 1991. Cloud top heights were photographed by a motor-driven camera which was fixed pointing downward at the central part of the aircraft fuselage floor. As a result, it was found that there were a fine structure of the periodic roughness of several hundred meters and an undulation of relatively longer cycles of several kilometers of cloud top heights. Furthermore, the relationship between the horizontal scale and cloud top height difference, and reflectance of stratocumulus clouds was discussed.

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1. Introduction

The shape, structure, and roughness or unevenness of cloud top surfaces have a significant influence upon solar radiation. In particular, clouds such as wide spread stratocumulus clouds over the ocean, and cirrus or cirrostratus clouds, and active anvil with cumulonimbus clouds can affect the climate through a radiation process. Many kinds of projects have been carried out to examine the relationship between clouds and radiation (ex. FIRE and EUCREX). There have been no observational results, however, concerning the fine structure of the cloud top surfaces of stratocumulus clouds. A stereophotographic method, in which the target clouds are photographed at two different separate sites on the ground surface simultaneously, has generally been used to analyze cloud structures (Magono et al., 1967a). The method has also been applied on aerial photographs (Magono et al., 1967b, c) and on pictures taken by a polar orbit satellite (Kikuchi and Kasai, 1968) as well as a geostationary meteorological satellite (Hasler, 1981; Mack et al., 1983; Hasler and Morris, 1986). Kikuchi et al. (1976) carried out the observations to clarify the cloud heights in the Antarctic area using a stereophotographic method, in which two whole sky lens cameras having a 7.5 mm focal length. Recently, furthermore, Kikuchi et al. (1991) analyzed the roughness or 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, in this case, were pointed in the vertical direction. These cloud observations, however, were not concerned with the relationship between the fine structure and radiative property of clouds.

To investigate the fine structure of roughness or unevenness of cloud top surfaces, and to obtain data about the relationship between the structure and reflectance, in situ observations using an aerial stereophotographic method to determine the roughness of the cloud top surface focussing on the winter stratocumulus clouds over the ocean were carried out from January 1989 to January 1991. The present research is part of the Cloud-Radiation Experiment of the World Climate Research Programme (WCRP) in Japan. In this paper, the results of preliminary investigations will be described.

2. Observational apparatus

The Cessna 404 (TITAN) aircraft as shown in Fig. 1 was used for this project. The arrangement of the 35 mm motor-driven cameras, pyranometers

Fig. 1. Photograph of observation aircraft used.

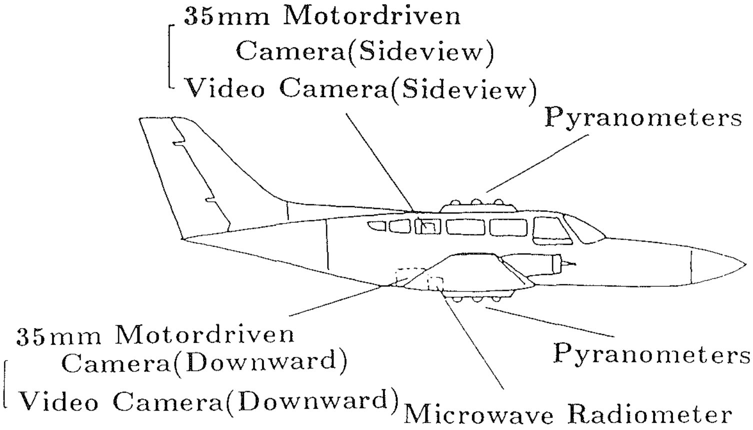
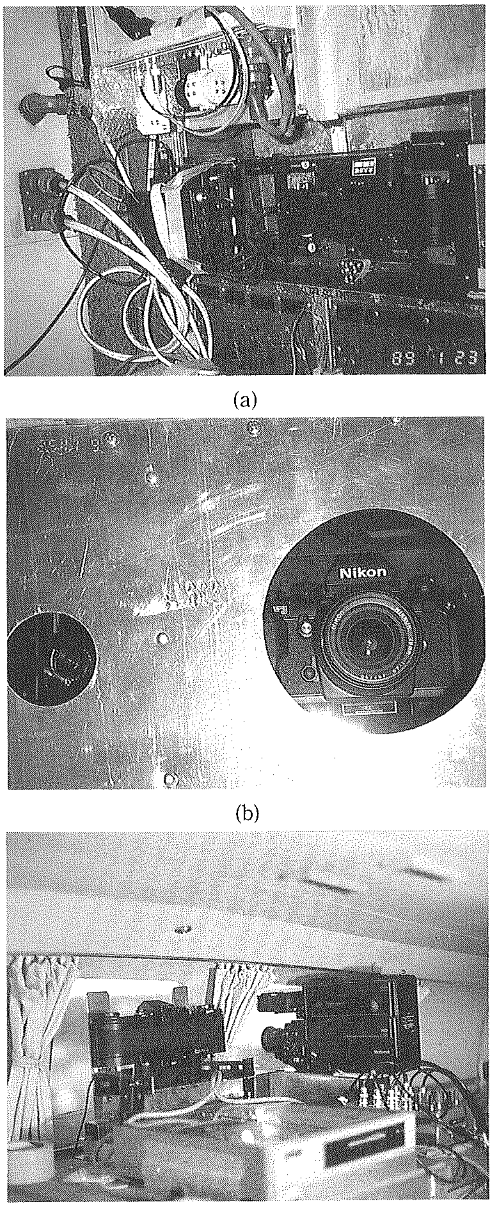


Fig. 2. Observational equipments installed in the aircraft.

and microwave radiometer on the aircraft is schematically shown in Fig. 2. A set of the 35 mm motor-driven camera of 28 mm focal length and video CCD camera was fixed pointing downward on the central part of the bottom of fuselage as shown in Fig. 3(a) and (b). A similar set of the 35 mm motor-driven camera and video camera was mounted pointing at an oblique angle on the frame, along the inside wall of the fuselage as shown in Fig. 3(c).

During the cloud observations, the aircraft flew with a constant altitude above



(a)

(b)

(c)

Fig. 3. (a) Motor-driven camera and microvideo camera fixed pointing downward at the floor of the aircraft fuselage. (b) Lens of both cameras seen from the ground surface. (c) Same as (a) but fixed pointing at an oblique angle to the wall of fuselage.

sea level and kept air speed as constant as possible. Aerial photographs were taken in constant time intervals continuously throughout the observation depending on the distance between the aircraft and the target clouds. The time interval was calculated so that 70% of the coverage area in a successive pair of photographs would overlap. In this case, the field of view of the picture was 46° as shown in Fig. 4 along the flight direction and 64° perpendicular to the direction. For analysis of the cloud top surface structure, the downward pointing motor driven camera was used and both the oblique camera and video camera were employed to obtain a general view of the target clouds. The photographs were carefully enlarged and corresponding points on a pair of photographs were marked. Corresponding points of 100 to 150 points were selected from each pair of photographs and were analyzed using an image analyzer which has an accuracy of approximately 2 or 3% in height as described in Kikuchi et al. (1991). Pyranometers and a microwave radiometer were operated and the data was analyzed by Tohoku University and Nagoya University, respectively.

3. Observational results

3.1 The case of the Wakasa Bay

The observations were carried out over the Wakasa Bay in the Japan Sea, Fukui Prefecture on the afternoon of January 24, 1989. Figure 5 represents the observational area and the flight courses. During the observation period, the Japan Islands were under an extratropical low off Sanriku coast as shown in Fig. 6 and the stratocumulus clouds and cumulus clouds closely extended in the observational area as shown in Fig. 7(a). The photograph of Fig. 7(a) was taken by a hand-held camera through the aircraft window and Fig. 7(b) was taken by

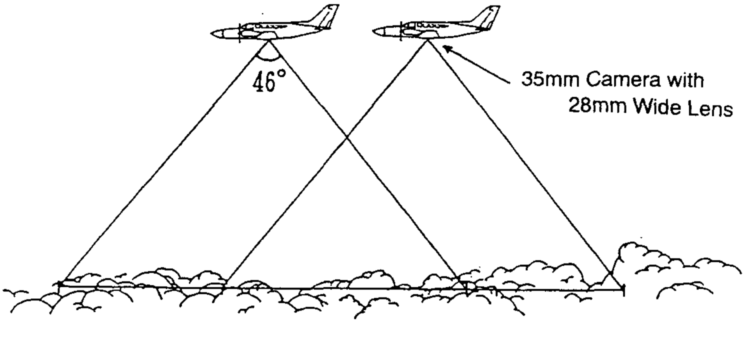


Fig. 4. Photographic operation of successive stereophotographs.

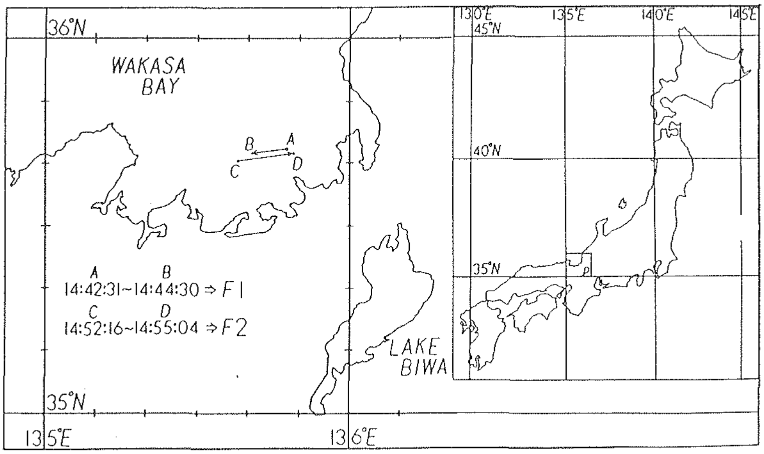


Fig. 5. Map of the observational area.

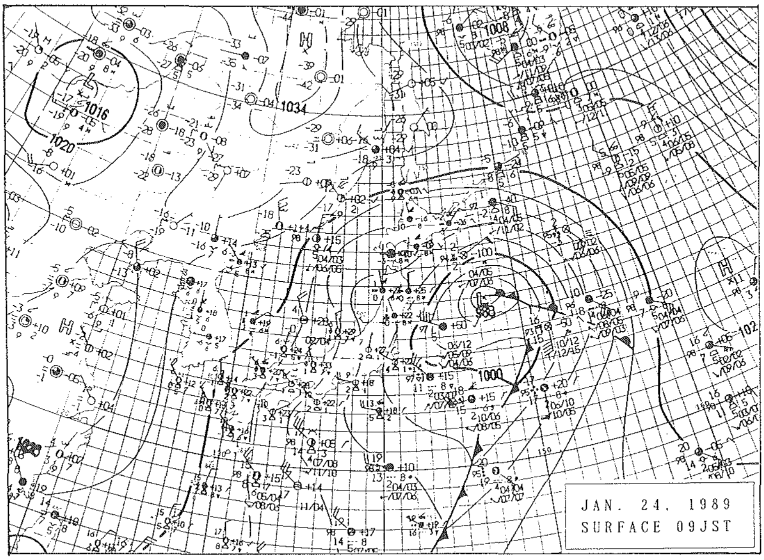
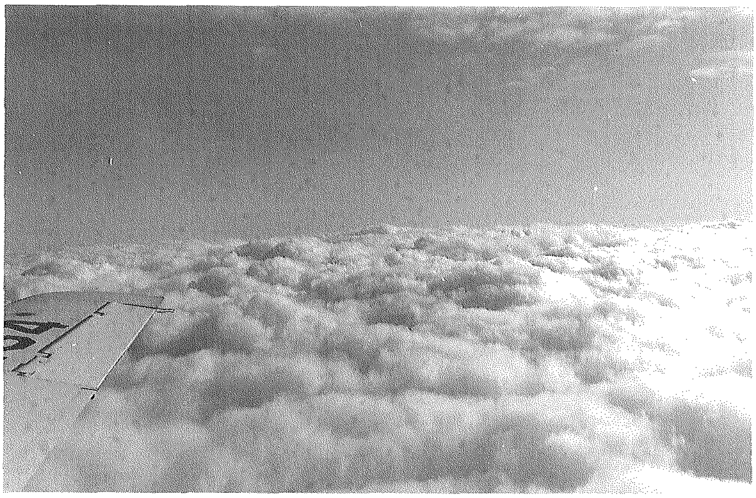


Fig. 6. Surface weather chart at 09JST January 24, 1989.

a downward pointing motor-driven camera. The cloud top height was estimated at 1,910 m a.s.l. (800 hPa) and the cloud top temperature was estimated to be approximately −10°C by the sounding curves on 0900JST at Yonago as shown in Fig. 8. Since the calculated lifting condensation level (LCL) was 1,100 m, we adopted this level as the cloud base height in this case. The cloud



(a)

(b)

Fig. 7. (a) Oblique photograph of cloud top surface of stratocumulus cloud. (b) Photograph taken by a pointing downward motor-driven camera.

particles were not ice crystals but supercooled droplets under the condition of the -10°C temperature. Throughout the observation, the fiight altitude was at a constant of 2,900 m. An observation analysis was carried out first along lines of A-B (8 km) (hereafter ; F1) from 1442 : 31 to 1444 : 30JST and C-D (12 km)

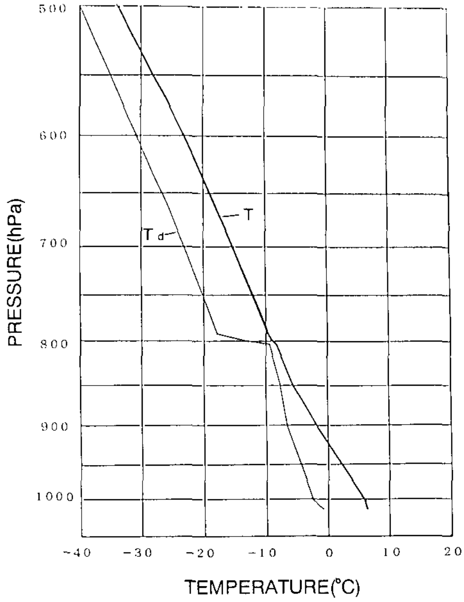


Fig. 8. Sounding curves at Yonago. 09JST January 24, 1989.

(hereafter ; F2) from 1452 : 16 to 1455 : 04JST, respectively. Figure 9 shows horizontal distributions of correspondence points of F2. In this figure, the abscissa and ordinate show the distance along flight course and width of 400 m apart from the flight course of "0" on the ordinate, respectively. Figure 10(a) and (b) shows the horizontal distributions of cloud top heights of F1 and F2 based on Fig. 9. Cloud top heights, in this example, are calculated for every 50 m. Original color grades corresponding to the cloud top heights are shown on the right-hand side. In this example, the highest cloud top heights were 2,173 m in F1 and 2,286 m in F2, respectively. The difference between the highest and the lowest cloud top heights was approximately 350 m in both cases. To clarify the roughness or unevenness of cloud top surfaces, the vertical cross sections of cloud top heights along the flight course ($y=0$ m) and at 300 m apart each ($y=\pm 300$ m) were conducted as shown in Fig. 11(a) and (b). In this figure, the ordinate and abscissa represents the cloud top heights measured in meters, and flight course measured in kilometers. It was clear that there were some periodic distributions with large amplitudes overlapped small roughness as seen in Figs. 10 and 11. To investigate the periodic distribution of these heights, and auto-correlation averaging 7 vertical cross sections at $y=\pm 300$ m, ± 200 m, ± 100 m and 0 m of the flight course in the case of F2 was calculated. The

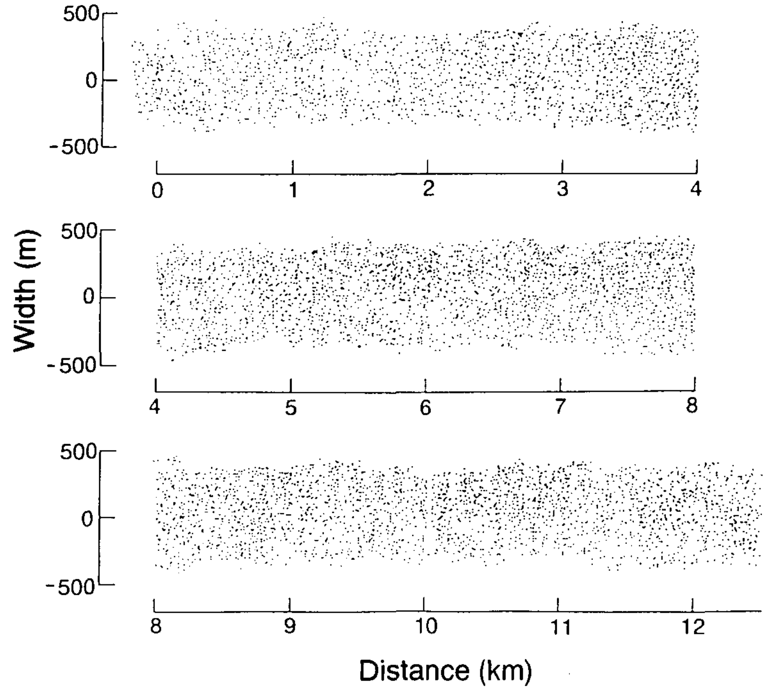


Fig. 9. Horizontal distributions of correspondence points. F2 (1452 : 16-1455 : 04 JST). January 24, 1989.

calculation was made at 4 km because the distance able to be analyzed was limited to 12 km. It was recognized that peaks existed at 1.3, 2.7 and 4 km as shown in Fig. 12.

3.2 The case of Amami Ohshima Island

The next observation was carried out in the area of about 50 km northwest of the Amami Ohshima Island, at approximately 1200JST on January 24, 1990 as shown in Fig. 13. The synoptic situation of this day was under the winter monsoon pressure pattern. The pressure gradient over the observational area, however, was weak as shown in Fig. 14. Stratocumulus clouds extended over the observational area as shown in Fig. 15(a) and (b). The photographs of Fig. 15(a) and (b) were taken by a hand-held camera and by a downward pointing motor-driven camera, respectively. The cloud top height was estimated at about 2,400 m a.s.l. (770 hPa) and cloud top temperature was estimated at approximately −7°C by the sounding curves on 0900JST at Naze, as shown in Fig. 16. An analysis was conducted on the data from 1158 : 05 to 1204 : 50JST

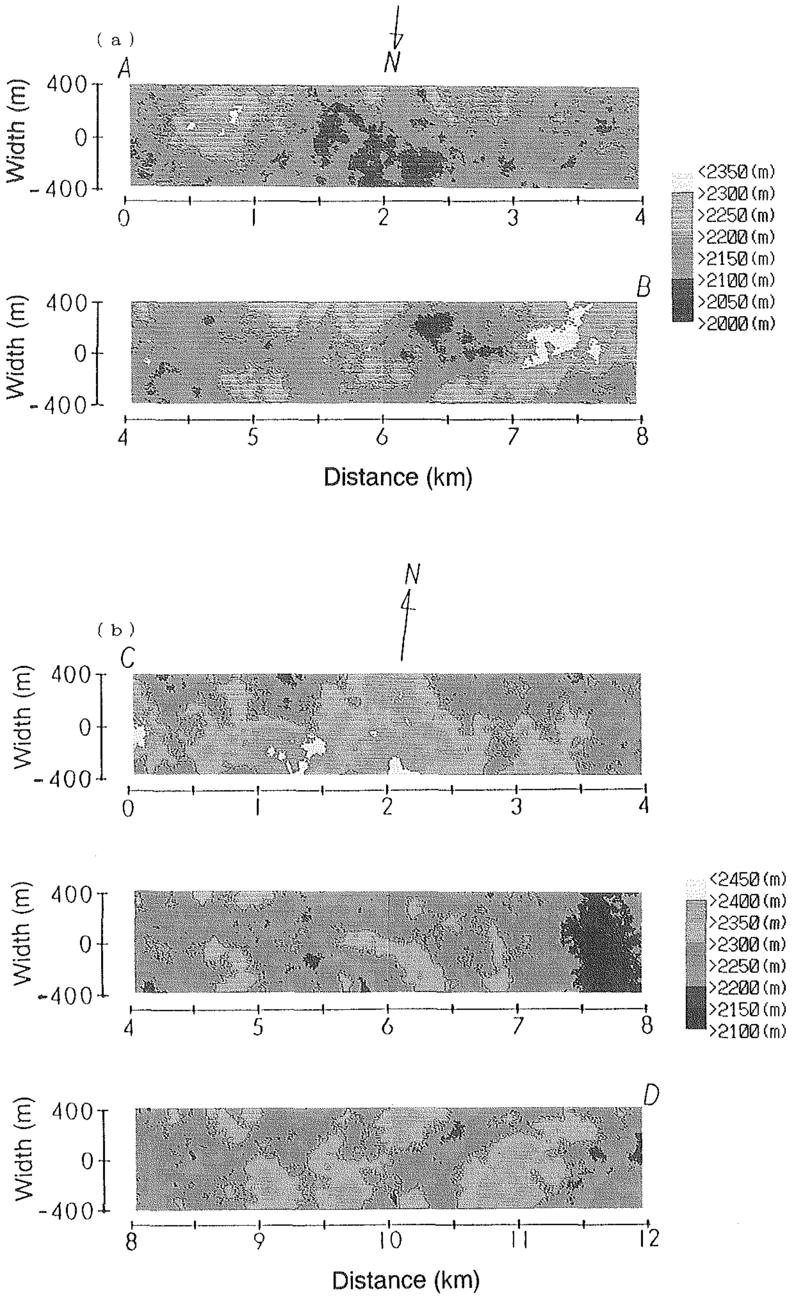


Fig. 10. Horizontal distributions of cloud top heights. (a) F1. (b) F2. January 24, 1989.

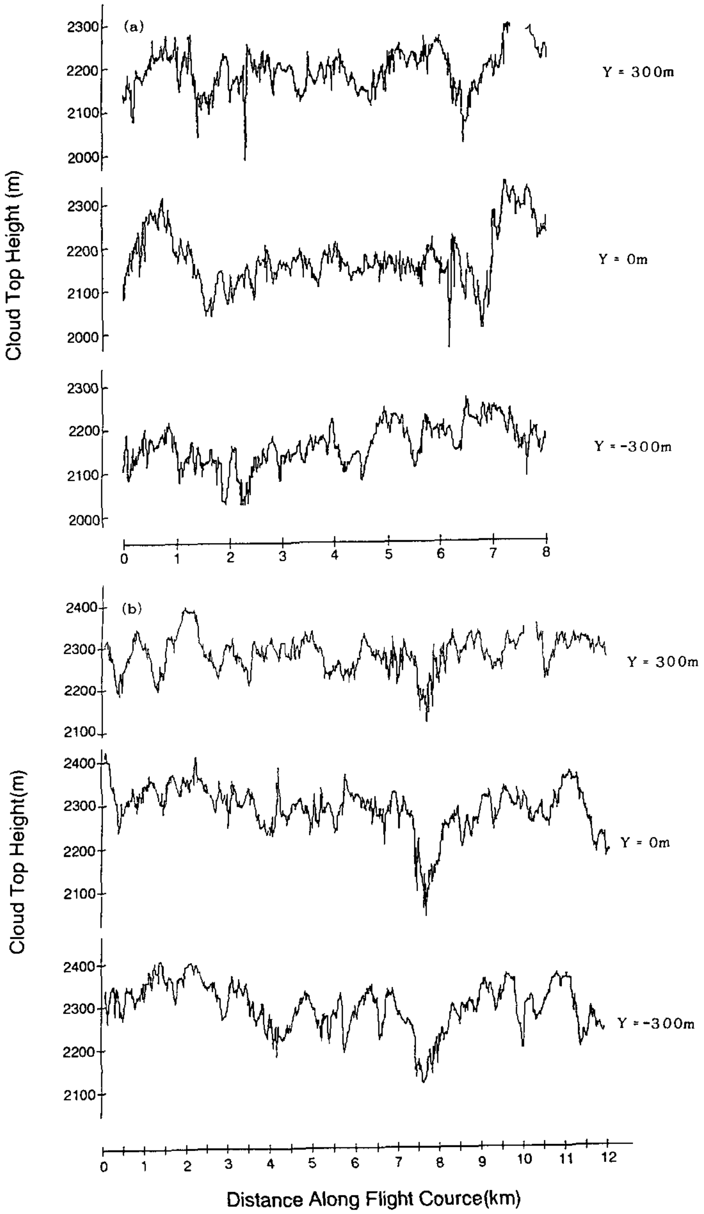


Fig. 11. Vertical cross sections of cloud top heights along the flight course. (a) F1. (b) F2. January 24, 1989.

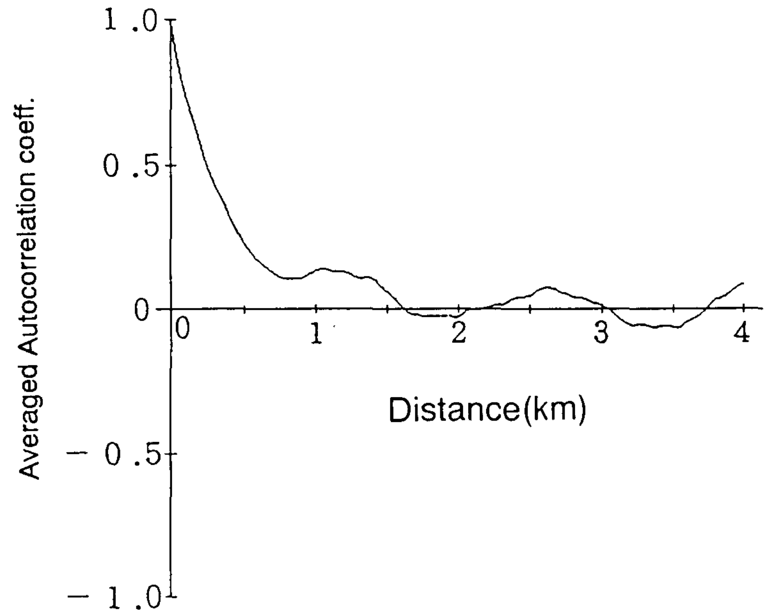


Fig. 12. Averaged auto-correlation coefficient along the flight course in the case of F2.

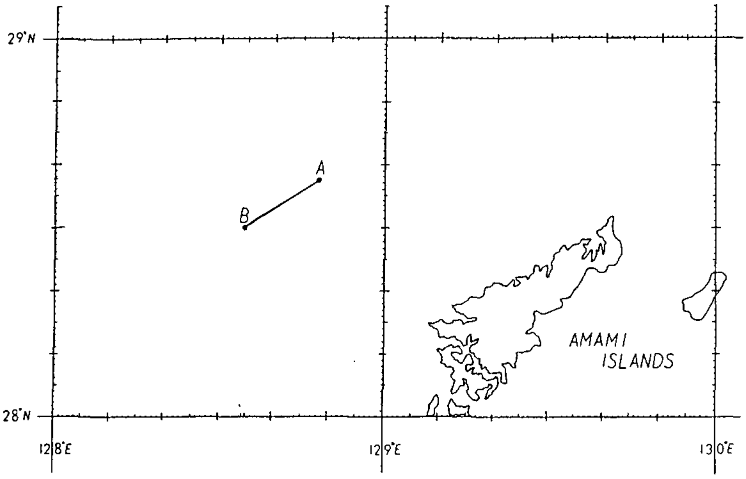


Fig. 13. Map of the observational area.

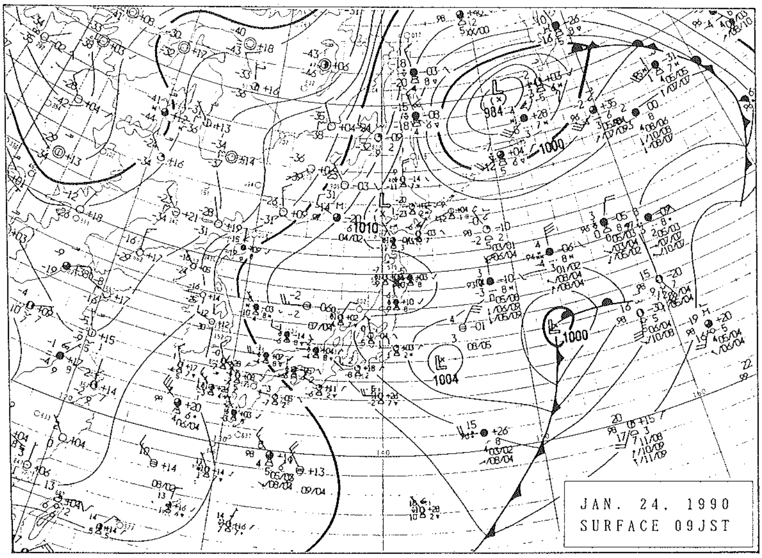


Fig. 14. Surface weather chart at 09JST January 24, 1990.

along the flight course from A to B as shown in Fig. 13. As the flight altitude of the observation aircraft was 4,100 m in this case, the width of an analytical area was approximately 2,000 m. The average cloud top height in the observational area was 2,202 m and the difference between the highest and the lowest cloud top heights was approximately 800 m. This value was twice as large of that of the previous case. Figure 17 represents the horizontal distributions of cloud top heights over an area of 2 km in width times 30 km in length. Cloud top heights in this case were calculated at every 50 m as shown in the color grades on the right-hand side as in the previous case. Figure 18 shows the vertical cross sections of cloud top heights along the flight course (y = 0 m) and at 600 m apart each (y = ±600 m). To investigate the dominant periodicity of the cloud top heights in this case, an auto-correlation averaging 9 vertical cross sections at y = ±800 m, ±600 m, ±400 m, ±200 m and 0 m of the flight course was calculated. The calculation was done at 10 km because the analytical distance was limited to 30 km. Figure 19 shows the calculation result. Since the calculation was carried out averaging 9 cross sections, the auto-correlation coefficient was relatively smaller than the previous case. As seen in this figure, it was clear that the periodicity was 1.5 km. It was understood therefore that smaller roughnesses or unevenesses were overlapped during this period.

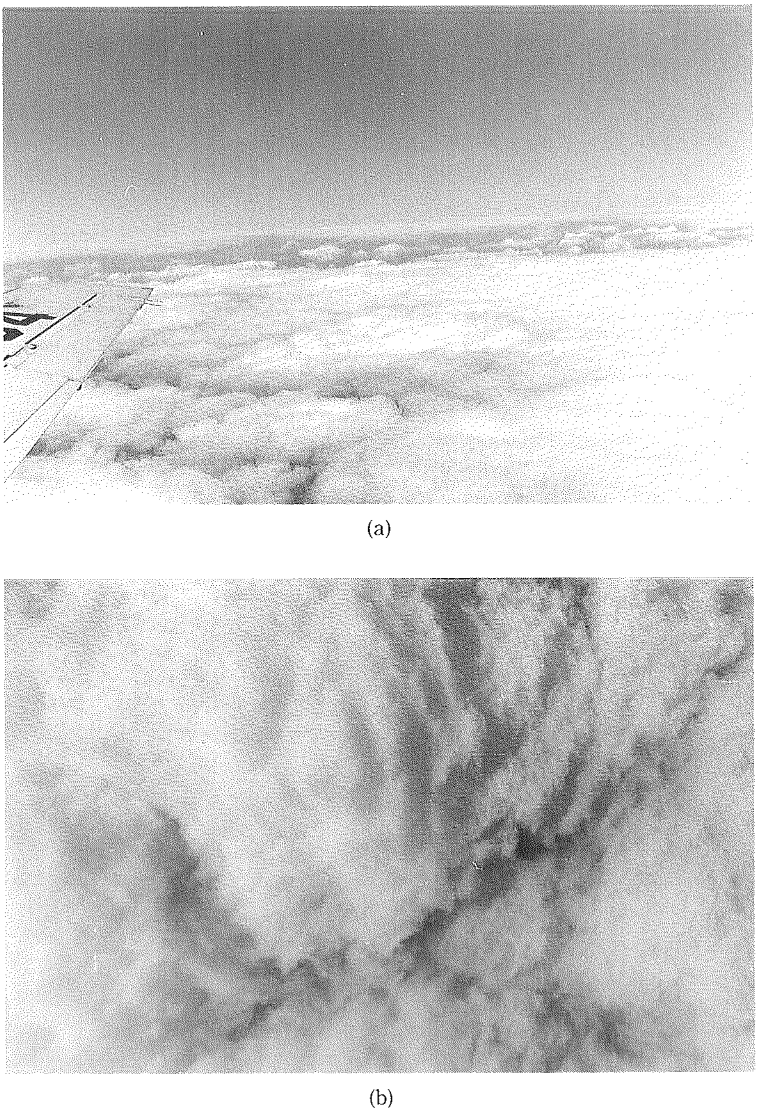


Fig. 15. (a) Oblique photograph of cloud top surface of stratocumulas cloud. (b) Photograph taken by a pointing downward motor-driven camera.

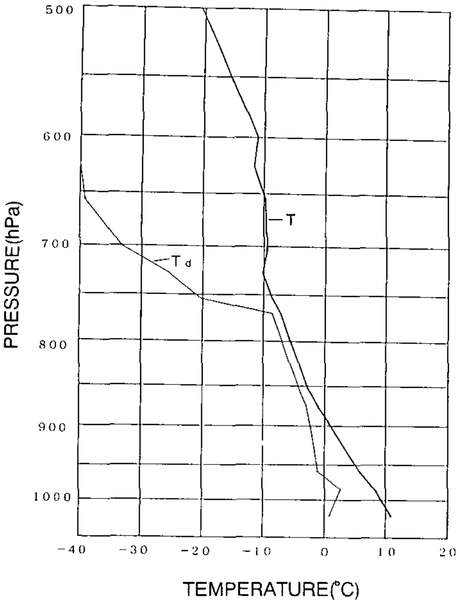


Fig. 16. Sounding curves at Naze. 09JST January 24, 1990.

3.3 *Relationship between the roughness of cloud top heights and reflectance on the cloud top surface*

Figure 20(a) and (b) represents the horizontal distributions of cloud thickness shown in Fig. 10 (a) and (b) and curves of the ratio of the outgoing radiative flux (F↑) to the incoming total radiative flux (F↓) (hereafter termed reflectance) as a function of distance along the flight course (Kikuchi et al., 1993). Since the radiative flux data was recorded at 5 second intervals and the aircraft speed relative to cloud top was approximately 82 m • sec^{-1}, the reflectance data was recorded at approximately 410 m intervals. As the flight altitude was 2,900 m and the average cloud top height was 2,173 m in F1 and 2,286 m in F2, the radiative flux data was recorded at an average of 700 m over the cloud top heights. Furthermore, it was reasonable to estimate that the cloud base height was constant at 1,100 m, based on the sounding curves at Yonago and aircraft observations on the widespread stratocumulus clouds over the ocean. The difference of cloud top heights, therefore, corresponds to the cloud thickness, because the cloud base height was constant. As a whole, the relationship between the horizontal distributions of cloud top heights and the curves of reflectance appears to be correlated to each other, as seen in the figure. More

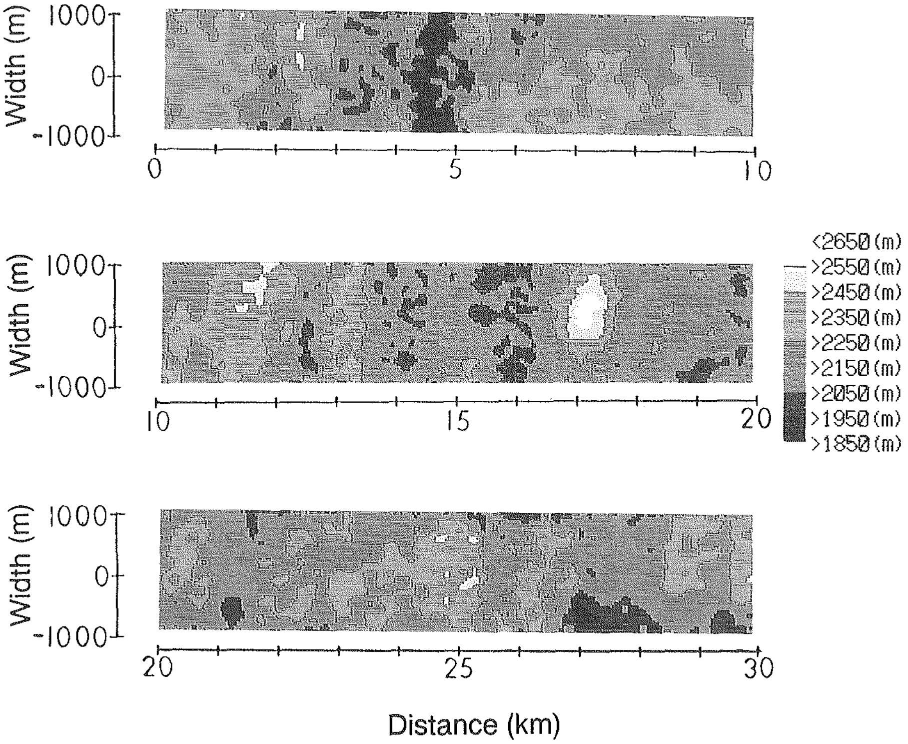


Fig. 17. Horizontal distributions of cloud top heights. January 24, 1990.

specifically, the reflectances were relatively high when the cloud thickness was thick and the cloud top surface concaved upward. On the contrary, the reflectances were relatively low when the cloud thickness was thin and cloud top surface convexed downward, as in F1 and F2. Upon further examination and in comparison with the horizontal distributions of cloud top heights and the reflectance, however, there were some differences in the cloud top heights (cloud thickness). Nevertheless the reflectances were approximately same. This fact means that the reflectance of clouds is not functioning on cloud thickness alone. So, we focussed our attention on the relationship between the reflectance and the sizes of horizontal scales and thickness of roughness or unevenness of the cloud top surface. With respect to the size of the upward convex of roughness or unevenness, we termed the representative cloud size as to the area of upward convex of elliptical shape owing to the short axis. Because of the northwesterly winter monsoon winds, the long axis of the elliptical shaped cloud was parallel to the prevailing wind direction. In the case of F1, there are four

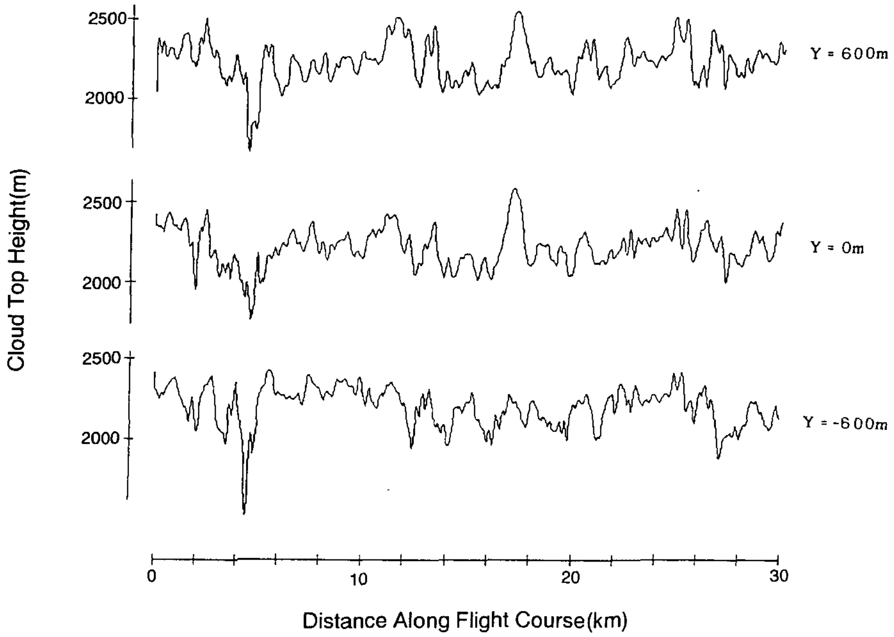


Fig. 18. Vertical cross sections of cloud top heights along the flight course. January 24, 1990.

upward convexes between the distances of 2.0 to 3.5 km and of 4.5 to 6.5 km with a reflectance of 0.65. Their convexes were approximately 0.7 km in horizontal dimension and 0.15 km in height. Furthermore, we noted other scale convexes having 0.5 km in horizontal dimension and 0.15 km in height. Their reflectance was approximately 0.6. In the case of F2, there was a different scale convex, of 1.3 km in horizontal dimension and 0.15 km in height and having 0.7 reflectance between 8.5 km and 12 km along the flight course. On the contrary, there was a downward concave with a reflectance of less than 0.5 between 7.0 and 9.0 km. In the area, the difference between the highest and lowest heights was more than 200 m per km. A tentative summary of these horizontal dimensions, height differences and reflectances, and their relation is shown in Fig. 21. After applying the same to Fig. 22, the relationship between the cloud thickness and reflectance could not be as clearly difined, in comparison with the previous case, especially the areas of upward convex at 17 km, downward concaves at 4 km and 27 km, respectively. Except these three areas, the relationship between the roughness of cloud top surface and reflectance will be introduced tentatively as shown in Fig. 23. Comparing Fig. 20 with Fig. 22, however, they do not show

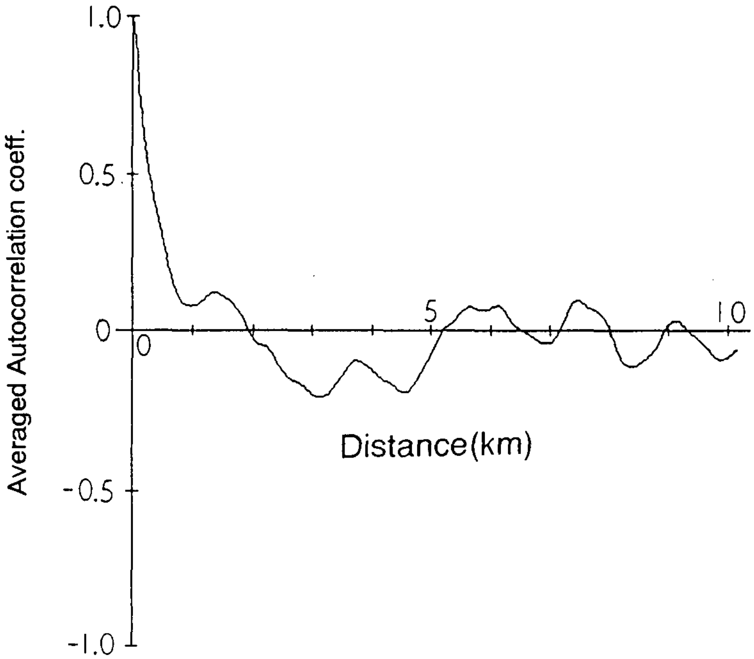


Fig. 19. Averaged auto-correlation coefficient along the flight course.

one to one correspondence in small scale.

4. Consideration and conclusions

The relationship between the roughness or unevenness of cloud top surface, that is cloud thickness, and radiation, and characteristic features of cloud top surfaces of stratocumulus clouds over the ocean by means of the stereophotographic method using an aircraft were investigated. In regards to the horizontal distributions of cloud top heights, even in the cases of stratocumulus clouds over the ocean, it was clear that there was the maximum difference of cloud top heights of approximately 300 m, as in the Wakasa Bay case and 800 m in the Amami Ohshima Island. Kikuchi et al. (1991) reported that there was a difference of cloud base heights of 300 m in the stratocumulus clouds over the land. It would be recognized, therefore that the cloud top heights and the cloud base heights were not flat or smooth even in the stratocumulus clouds. In any case, it was clarified that the cloud top heights had some prevailing periodicities. If we supposed that the scale of prevailing periodicities reflected the horizontal

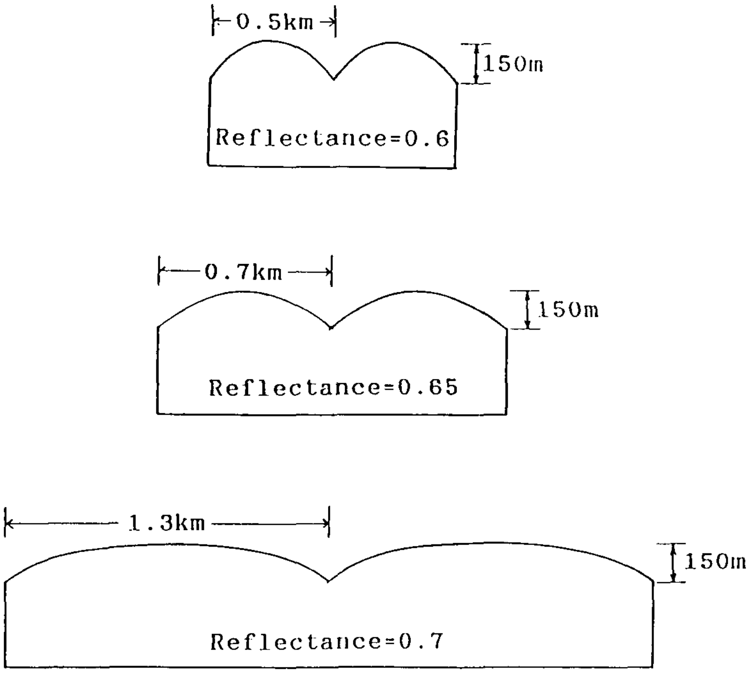


Fig. 21. Schematic figure of stratocumulus clouds over the Wakasa Bay showing the relationship between horizontal dimensions, height differences, and reflectance.

scale of free convection, the periodicity could be used to compare the ratio of horizontal to vertical dimension of Bénard convection. From the sounding curves, if we select 2.4 km as the vertical dimension of convection, the horizontal dimension would be 5 to 7.5 km, because the horizontal dimention is 2 or 3 times that of the vertical dimention. It is impossible, however to introduce a predominant periodicity of 7.5 km from the observational length of 12 km in the case of Wakasa Bay. The predominant periodicity was shorter than the previous one. It was thought that the periodicity would be decided by smaller scale turbulences.

Concerning the relationship between the horizontal distributions of cloud top heights and reflectances, both elements appeared to be correlated to each other as a whole. Based on the analyses of the horizontal dimentions, height differences, and reflectances, their relationship was drafted tentatively as shown in Figs. 21 and 23. The fact that the large height differences had upward convexes and downward concaves in limited small scales, however, did not contribute to the reflectance. For instance, they recognized at 4 km along the

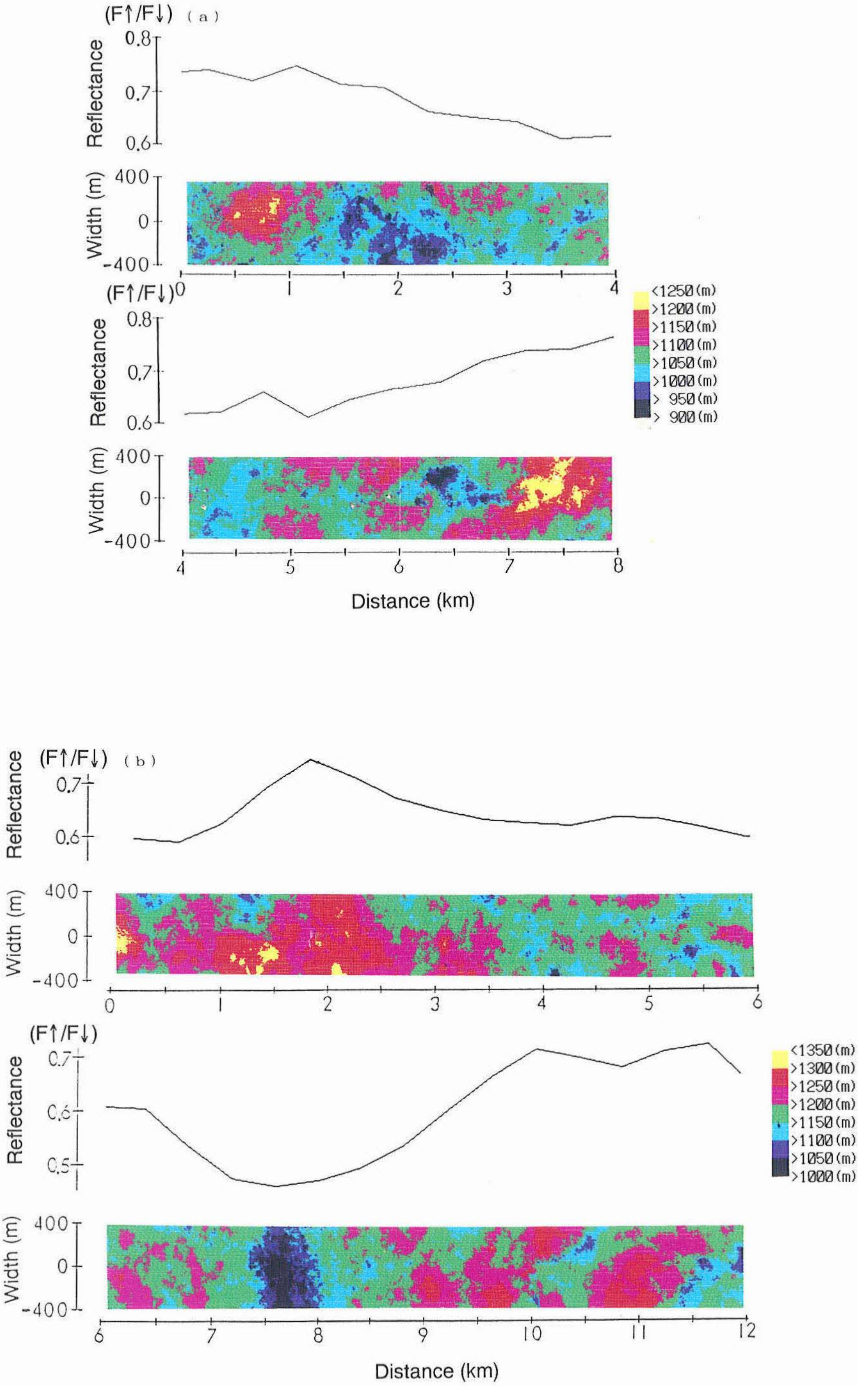


Fig. 20. Horizontal distributions of cloud thickness and reflectance. (a) F1. (b) F2. Janury 24, 1989.

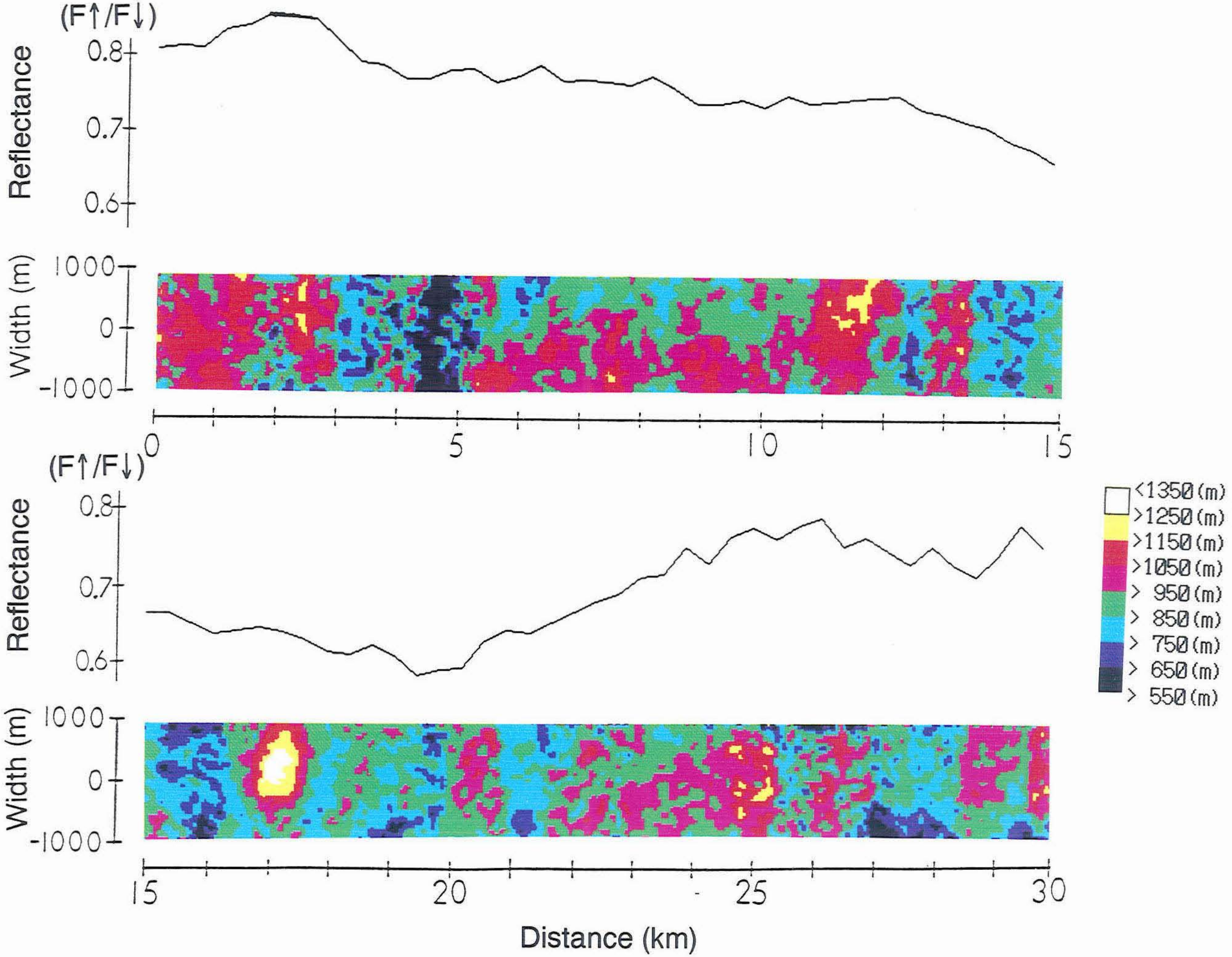


Fig. 22. Horizontal distributions of cloud thickness and reflectance. January 24, 1990.

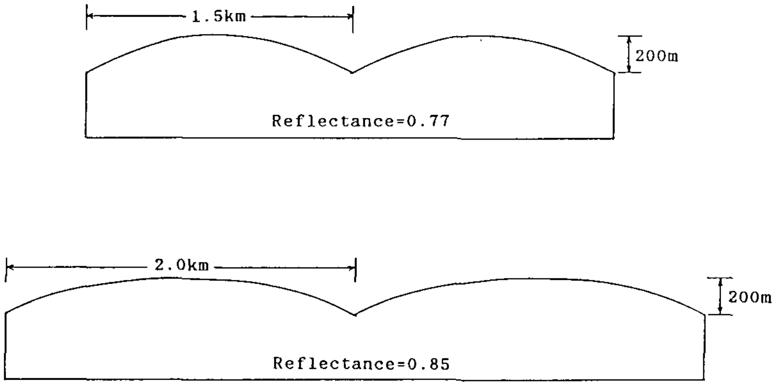


Fig. 23. Schematic figure of stratocumulus clouds over around Amami Ohshima Island showing the relationship between horizontal dimensions, height differences, and reflectances.

flight course that a 0.7 km in height difference and 1 km an horizontal dimension of a downward concave existed, at 17 km that a 0.5 km height difference and 2 km in horizontal dimension of an upward convex existed, and at 27 km that a 0.55 km height difference and 2 km in horizontal dimension of a downward concave existed, respectively. The ratios of height difference to horizontal dimension of convexes and concaves were 0.7 at 4 km, 0.25 at 17 km, and 0.275 at 27 km along the flight course. This result might inform us that the roughness or unevenness of cloud top surface of the isolated upward convex and downward concave having a ratio larger than 0.25, would not contribute to reflectance.

Further considerations will be described in another paper (Kikuchi et al., 1993).

Acknowledgments

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