Relationship between Topography and Daytime Cloud Activity around Tibetan Plateau

Yasunori KUROSAKI
Institute of Geoscience, University of Tsukuba, Tsukuba, Japan

and

Fujio KIMURA1
Institute of Geoscience, University of Tsukuba, Tsukuba, Japan

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Abstract

The relationship between topography and daytime cloud activity over the Tibetan Plateau and surrounding areas was examined by using Geostationary Meteorological Satellite (GMS) Visible (VIS) and Infrared (IR) images during the premonsoon, and monsoon periods in 1998. Previous studies using IR images have already confirmed the strong diurnal variation of convective activity over the Tibetan Plateau. This study relies primarily on VIS images to analyze daytime cloud distribution because VIS images are more adaptable to low-level clouds and they offer better spatial resolution than IR images. IR images are used to judge whether cloud tops are high or low. High-level clouds are prominent over the large-scale (100–300 km) mountain ranges, but fewer clouds are observed in the major valleys in the plateau during premonsoon and monsoon periods at 15 Local Solar Time (LST), when the amount of cloud cover is at its maximum from 09 LST to 15 LST. However, the relationship between cloud distribution and topography is not always clear when the horizontal scale of the topography is less than 100 km.

Less cloud coverage was observed over the plateau in the morning during the premonsoon period. On the contrary, clouds frequently appeared over the southeastern part of the plateau in the morning during the monsoon period. Low-level clouds often cover the southern slope of the Himalayas, and the frequency of cloud coverage exceeds 75% at 15 LST in the monsoon period. While the cloud tops are growing high elevation in the afternoon over the plateau, low-level clouds cover the southern slope of the Himalayas through the daytime (09–15 LST).

1. Introduction

The Tibetan Plateau affects the circulation above the plateau and in the surrounding areas as an elevated heat source during the spring and summer seasons. This effect is important for the onset and maintenance of the Asian summer monsoon (e.g., Yanai et al. 1992). The mechanisms of atmospheric heating caused by the plateau are different in the premonsoon and monsoon periods. Since a large sensible heat flux and a deep mixed layer are observed over the plateau during the premonsoon period, sensible heat from the surface is presumed to be directly transported into the upper-level atmo-
sphere by dry convection (Yanai and Li 1994). During the monsoon period, on the other hand, the latent surface heat flux and precipitation become large, and quite active cumulus convection can then be observed using the infrared (IR) sensor of the Geostationary Meteorological Satellite (GMS) (Murakami 1983; Yanai and Li 1994; Ueno 1998; Kuwagata et al. 2001; Fujinami and Yasunari 2001). These facts indicate that latent heat released by cumulus convection is the major heat source during the monsoon period. Murakami (1983) demonstrated that there was intense diurnal variation in the deep convective activity that took place over the southern part of the Tibetan Plateau by analyzing GMS IR images taken in July and August 1979. The convective activity reached the daily minimum at 09 Local Solar Time (LST), i.e., 03 UTC, and the maximum at 18 LST (12 UTC). Daytime convection was active over the plateau, but the convection was active at night over the surrounding areas rather than over the plateau (Yanai and Li 1994). Fujinami and Yasunari (2001) mentioned the strong diurnal cloud activity in the premonsoon period, as well as in the monsoon period. They inspected the static stability in the lower atmosphere during the premonsoon period, and speculated that the cloud is induced by the shallow convection.

Cloud activity agrees with the major topography in the plateau, which has a valley width of 100–300 km (Ueno 1998; Kuwagata et al. 2001). Ueno (1998) showed that daytime (nighttime) precipitation appears over major mountain (valley) regions through the precipitation data estimated by GMS IR image during the monsoon period in 1993. Kuwagata et al. (2001) obtained the temporal and spatial distribution of clouds, which was similar to the precipitation distribution obtained by Ueno (1998). They insisted that the horizontal cloud distribution corresponding to the major topographical features is caused by thermally induced local circulation that transported moisture from the bottom of the valley to the mountain ridges.

Yanai and Li (1994) analyzed data obtained from the First GARP (Global Atmospheric Research Program) Global Experiment (FGGE), and the Qinghai-Xizang Plateau Meteorology Experiment (QXPMEX), to show that the daytime moisture decreased over nearly the whole Tibetan Plateau, and they proposed the theory that the horizontal advection of the dry and cold atmosphere caused this phenomenon. Recent studies, however, indicate that the daytime moisture decrease reported by Yanai and Li (1994) was not a phenomenon occurring on a plateau scale but rather one occurring on a major topographical scale (100–300 km). Kuwagata et al. (2001) discussed the horizontal transport of moisture by thermally induced local circulation in the major topography of the Tibetan Plateau after showing that most observation stations are located in valley regions. By analyzing GPS precipitable water, Takagi et al. (2000) demonstrated that precipitable water decreases in the daytime at Lhasa, which is located at the bottom of a valley (shown in Fig. 1b). By using data from a GMS water vapor channel (IR3), Kuwagata et al. (2001) and Yatagai (2001) showed that there had been a decrease of water vapor in major valley regions, and an increase in major mountainous regions. Temporal and spatial distributions of water vapor shown in these two studies corresponded to the temporal and spatial distributions of convective clouds shown by Ueno (1998) and Kuwagata et al. (2001). Kuwagata et al. (2001) conducted a simple two-dimensional numerical experiment as well and obtained a result indicating that the widths of major valleys (100–300 km) in the Tibetan Plateau were suitable for horizontal water vapor transport by thermally induced local circulation. This experiment proves that thermally induced local circulation is an important cause of the diurnal variation in convection over the Tibetan Plateau.

A large amount of precipitation has been observed with rain gages over the southern slope of the Himalayas. Yasunari and Fujii (1983) presented a heavy precipitation map in Nepal showing that areas exceeding 2,000 mm are distributed in an east-west direction along the Himalayas during four months from June to September. This fact indicates that the southern slope of the Himalayas is an enormous heat source. However, the details concerning the amount of heat and its temporal and spatial distribution were not clarified. The average amount of precipitation at Lhajung (27°53′N, 86°50′E, 4,420 m), which is located in a valley,
is 10.3 mm month\(^{-1}\) and 145.7 mm month\(^{-1}\) in May and July, respectively (according to the Japanese Society of Snow and Ice 1976, 1978). In the mountainous regions around Lhajung, on the other hand, the amount of precipitation during the monsoon period is several times larger than that at Lhajung (Ageta 1976). This large difference in the amount of precipitation in the mountains and in the valley regions indicates that the data obtained by rain gages have some problems of spatial representation. The numerical model also has a problem in the reproduction of precipitation in this region because the southern slope of the Himalayas is too steep for a numerical grid system. Yoshi-kane et al. (2001) obtained excessive precipitation in their numerical experiment, compared to the precipitation data of CMAP (Xie and Arkin 1997). While they are doubtful that convective parameterization induces excessive precipitation over a steep slope, they have been unable to find a definitive answer to this question.

Although Ueno (1998) and Kuwagata et al. (2001) investigated the relationship between cloud activity and major topography over the plateau during the monsoon period, none has focused on the one during the premonsoon period. Low-level clouds (i.e., the altitude of the cloud top is low) have not been studied as much as deep convection. However, low-level clouds should be studied, too, because cloud activity has a large effect on atmospheric heat through the radiative process. The relationship of cloud distribution and meso-scale topography (less than 100 km) has not been investigated well with realistic data. Uyeda et al. (2001) reported precipitation radar observation around Naqu, but the orographic effects on the precipitation is unclear because of the limitation of the sounding area. Time variations of cloud amount, and cloud-top elevation over the southern slope of the Himalayas, have not been investigated by using satellite image, while rain gage data has the problem of spatial representation.

The objective of this study is to clarify the relationship between topography and daytime cloud activity over the Tibetan Plateau and surrounding areas. Cloud activities during the premonsoon and monsoon periods will be investigated, focusing on the following subjects: (1) the relationship of cloud activity and meso-scale topography (less than 100 km) as well as the major topography (100–300 km) in the plateau; (2) low-level clouds as well as high-level clouds (i.e., high cloud-top elevation); and, (3) the cloud activity over the southern slope of Himalayas.

To detect the detailed cloud activity over the complex topography, this study especially introduced GMS Visible (VIS) images, which have two advantages compared to GMS IR images. The VIS images have higher spatial resolution, and they are easy to detect low-level clouds. Only daytime cloud activities, however, were investigated because VIS images were primarily used for this study.

In our analysis, Sections 4.1, 4.2, and 4.3 deal with the daytime hourly horizontal cloud distribution, which is investigated with GMS VIS image. Sections 4.4 and 4.5 deal with cloud-top elevation. Clouds observed by VIS image can be categorized as low- or high-level clouds by using an equivalent black body temperature (TBB) obtained with a GMS IR image.

2. Topography

The Tibetan Plateau is located in the vicinity of 75\(^\circ\)–105\(^\circ\)E, 28\(^\circ\)–40\(^\circ\)N, as shown in Fig. 1a. The topography of the analysis domain is shown in Fig. 1b, corresponding to the solid-lined box (85\(^\circ\)–95\(^\circ\)E, 25\(^\circ\)–35\(^\circ\)N) in Fig. 1a, where the central Tibetan Plateau, the Himalayas, and the Hindustan Plain are located. The characteristics of the topography in this domain are: (1) the high altitude of the Tibetan Plateau (about 4,500 m a.s.l.); (2) the large undulation in the north-south direction of the plateau; and, (3) the southern steep slope of the Himalayas with a gradient of about 5,000 m in altitude per 100 km (near 27\(^\circ\)–28\(^\circ\)N). The second characteristic mentioned above is caused by the fact that most of the major mountain ranges and major valleys in the plateau are aligned in an east-west direction. They are the Tanggula Range (Region A), the Nyainqentanglha Range (Region B), the Yarlung-Zangbo River (Region C), and a valley dividing the Tanggula and Nyainqentanglha Ranges (Region D). The length of these ranges and valleys is over 1,000 km, and their width is about 100–300 km. Many peaks of the Himalayas, for example, Mt. Everest and Mt. Kangchenjunga, are also located along the east-west line on the
southern edge of the Tibetan Plateau, as shown in Fig. 1b.

3. Data and analysis

The cloud activity around the Tibetan Plateau was analyzed using Visible channel (0.55–0.90 μm, VIS) and IR1 channel (10.5–11.5 μm, IR) images of the Geostationary Meteorological Satellite (GMS).

At first, cloud-covered areas are determined by using hourly albedo data obtained by a VIS image (Section 3.3), and cloud-cover frequency (defined in Section 3.4) at each hour is estimated for each grid point in order to investigate the daytime variation of the cloud distribution. Second, cloud-top elevation is estimated by TBB data obtained by a GMS IR image. The cloud-top elevation is estimated for each grid point from the cloud-top temperature, which is defined as the average TBB obtained only when the cloud cover is observed by a VIS image, referring to the temperature profiles of the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data (Section 3.5).

3.1 Horizontal resolution

A GMS image for the analysis, provided by Kochi University, was geometrically resampled at 0.05-degree (about 5 km) intervals. The grid intervals of the original VIS and IR images (i.e., before resampling) at the area just under the GMS (0°–95°E, 25°–35°N) indicates the area shown in Fig. 1b. The analysis domain. Contours indicate 300 m and 600 m a.s.l. (white dashed line), 3,000 m a.s.l. (white solid line), 4,850 m a.s.l. (black dotted line), 5,300 m a.s.l. (black dashed line), and 6,000 m a.s.l. (black solid line). Major mountain regions A (Tanggula Range) and B (Nyainqentanglha Range) are indicated by thick solid lines. Major valley regions C (Yarlung-Zangbo River) and D (no name) are indicated by thick dash-dot lines.

3.2 Analysis period and hour

Two periods, premonsoon (May 01–31, 1998) and monsoon (June 27–July 31, 1998), were selected for the analysis, referring to observations made during the GEWEX Asian Monsoon Experiment-Intensive Observational Period (GAME-IOP). Endo et al. (1999) have reported...
that the onset of the monsoon seems to be around June 13, as estimated by radio-sonde and rain gage observations at Amdo (shown in Fig. 1b). The premonsoon and the monsoon periods defined in this study correspond to the declining time of the spring cloud activity and the peak of the summer cloud activity in Fuji-nami and Yasunari (2001) mentioned above, respectively.

Analysis was limited from 09 LST to 15 LST (i.e., from 03 UTC to 09 UTC), when the solar elevation angle was high enough to allow identification of clouds using VIS images. Table 1 shows the number of available images, approximately 30 per hour during both periods.

3.3 Detection of the cloud cover

In this study, the cloud-covered areas were determined by albedo data obtained by VIS images. Since these data depend on the solar zenith angle, a correction for the albedo data was carried out by Eq. (1), following Rossow and Garder (1993). The maximum correction ratio $1/\cos \theta$ in the analysis period was about 1.39 at the point of (30°N, 90°E), which is the center of the analysis domain.

$$a' = \frac{a}{\cos \theta},$$

where $a$ is the original albedo data obtained by a GMS VIS sensor, $a'$ is the corrected albedo value, and $\theta$ is the solar zenith angle.

The threshold of albedo with or without cloud cover is determined as 0.40:

- cloud cover when $a' \geq 0.40$,
- land-surface when $a' < 0.40$.

According to previous studies, the albedo of any typical land surface is less than 0.40 except in the case of snow cover.

By the above method, snow-covered areas cannot be distinguished from cloud-covered ones. Therefore, the probability of snow cover must always be taken into account when there is a very high frequency of high albedo throughout the daytime.

3.4 Definition of cloud-cover frequency

Cloud-cover frequency is estimated in order to investigate the daytime evolution of the cloud distribution. Cloud-cover frequency is defined as the percentage of cloud cover times to the total number of available images for each grid point at each hour.

3.5 Definition of high-level clouds and low-level clouds

The cloud-top temperature at each grid point is defined as Eq. (3), which is the average TBB obtained by IR images only when the cloud cover is detected by using VIS images, as mentioned in Section 3.3.

$$\frac{\sum \delta_i TBB}{\sum \delta_i},$$

where $\delta_i = 1$ when $a' \geq 0.40$, $\delta_i = 0$ when $a' < 0.40$.

By using this cloud-top temperature defined by Eq. (3), clouds are roughly classified into two categories. One is high-level clouds, whose cloud-top temperature is less than 250 K, and the other is low-level clouds, whose temperature is over 250 K. The elevation of the cloud top is approximately estimated from the mean TBB by Eq. (3) and the temperature profile. The temperature profile is assumed to be that at the center of the analysis domain (30°N, 90°E) given by the monthly mean NCEP/NCAR reanalysis data in 1998 (Table 2). The elevations corresponding to 250 K are 8,200 m a.s.l., and 9,500 m a.s.l. during the premonsoon and monsoon periods, respectively. The north-south differences of the elevations at 250 K between 25°N and 35°N are 1,000 m and 500 m along 90°E during the premonsoon and monsoon periods, respectively.

4. Results

4.1 Daytime variation of cloud distribution

Figure 2 shows the horizontal distributions of the cloud-cover frequency (%) at 09 LST, 12 LST, and 15 LST (03 UTC, 06 UTC, and 09 UTC).
09 UTC, respectively) during the premonsoon period (Figs. 2a,b,c) and the monsoon period (Figs. 2d,e,f) in 1998, respectively. Figure 3 explains the meso-scale (less than 100 km) cloud distributions at 09 LST (Fig. 3b) and 15 LST (Fig. 3c) during the monsoon period. The topography in this area is shown in Fig. 3a. Figures 3a,b, and c are close-up images of Fig. 1b, Fig. 2d, and Fig. 2f, respectively.

As mentioned in Section 3.3, snow-covered areas cannot be distinguished from cloud-covered ones. In Figs. 2 and 3, several snow-covered areas may be included in high-albedo areas, which are defined as cloud-covered areas by Eq. (2). This is, however, an insignificant problem when discussing the temporal variation of horizontal cloud distribution by using the definition of Eq. (2) because snow-covered areas are reasonably expected to be small, as mentioned at the end of this section.

The diurnal variations of the cloud-cover frequency and the cloud-covered area during the daytime over the Tibetan Plateau were examined for each period, i.e., the premonsoon period (Figs. 2a,b,c) and the monsoon period (Figs. 2d,e,f). As shown in Fig. 2a, cloud-cover frequency is in the range between 0% and 25% at most areas over the plateau. This means that only a small amount of cloud cover is observed at 09 LST during the premonsoon period. At 12 LST (Fig. 2b), however, the amount of cloud cover increases around the northeastern part of the plateau. At 15 LST (Fig. 2c), cloud-cover frequency becomes quite high over a large area of the plateau. In contrast with Fig. 2a (09 LST in the premonsoon period), cloud-cover frequency is relatively high at 09 LST during the monsoon period (Fig. 2d), when the frequency is in the range of 25–50% in most areas of the plateau. At 12 LST (Fig. 2e), the frequency distribution becomes smaller than that at 09 LST, and only small areas in the range of 25–50% are scattered in the domain. The amount of cloud cover achieves its maximum at 15 LST in the analysis hours (09–15 LST), commonly during premonsoon and monsoon periods.

In the spatial distribution of cloud-cover frequency, seasonal dependency can be clearly observed at 15 LST over the plateau. During the premonsoon period (Fig. 2c), a large amount of cloud cover is distributed in the northern area. During the monsoon period (Fig. 2f), on the contrary, the amount of cloud cover is larger in the southern area than in the northern area. At 09 LST as well, a seasonal difference in spatial cloud distribution is observed. Clouds rarely appear in the premonsoon period (Fig. 2a). In the monsoon period, clouds frequently appear over the southeastern part of the plateau (Fig. 2d), especially in the southern area of Region B (Nyainqentanglha Range), shown by BOX II in Fig. 3b, which is a close-up of the image in Fig. 2d.

Without seasonal difference, cloud distribution corresponds to the major topography, having valley width of 100–300 km, in the plateau at 15 LST during premonsoon (Fig. 2c) and monsoon (Fig. 2f) periods, although north-south distribution has seasonal difference. The

<table>
<thead>
<tr>
<th>May Air Temperature</th>
<th>Height</th>
<th>North-South Difference</th>
<th>July Air Temperature</th>
<th>Height</th>
<th>North-South Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>220 K</td>
<td>12,900 m (8,400 m)</td>
<td>1,000 m</td>
<td>220 K</td>
<td>13,700 m (9,140 m)</td>
<td>–200 m</td>
</tr>
<tr>
<td>230 K</td>
<td>11,200 m (6,700 m)</td>
<td>1,200 m</td>
<td>230 K</td>
<td>12,400 m (7,770 m)</td>
<td>100 m</td>
</tr>
<tr>
<td>240 K</td>
<td>9,700 m (5,200 m)</td>
<td>1,200 m</td>
<td>240 K</td>
<td>11,000 m (6,410 m)</td>
<td>300 m</td>
</tr>
<tr>
<td>250 K</td>
<td>8,200 m (3,700 m)</td>
<td>1,000 m</td>
<td>250 K</td>
<td>9,500 m (4,920 m)</td>
<td>500 m</td>
</tr>
<tr>
<td>260 K</td>
<td>6,800 m (2,300 m)</td>
<td>700 m</td>
<td>260 K</td>
<td>7,900 m (3,300 m)</td>
<td>500 m</td>
</tr>
<tr>
<td>270 K</td>
<td>5,400 m (900 m)</td>
<td>300 m</td>
<td>270 K</td>
<td>6,400 m (1,730 m)</td>
<td>100 m</td>
</tr>
</tbody>
</table>
frequency is high along the major mountain ranges, i.e., Region A (Tanggula Range) and Region B (Nyainqentanglha Range). On the contrary, the frequency is quite low over the major valleys, such as Region C (Yarlung-Zangbo River), and Region D.

In the area of meso-scale topography (less than 100 km), however, cloud distribution shows agreement with the topography only in some limited sections. Cloud distribution does not show agreement with the topography in the region around Amdo and Naqu shown by BOX I in Fig. 3. However, cloud-cover frequency shows agreement with the topography in the region around Lhasa shown by BOX II in Fig. 3, which has prominent diurnal variation during the monsoon period. High-frequency areas are partially distributed in the valley region in BOX II at 09 LST, as shown in Fig. 3b, while Fig. 3c clearly shows quite lower frequency in the whole valley region than in the surrounding mountain regions at 15 LST.

Along the southern slope of the Himalayas, cloud-cover frequency is quite high at 15 LST in comparison with those of 09 LST and 12 LST during the premonsoon and monsoon periods. The southern slope can be recognized in the figures as a band area located between the contour line of 300 m along about 27°N, and the peaks of the Himalayas along about 28°N (see Chapter 2). Cloud-cover frequency is quite high, especially over the area above 3,000 m a.s.l. Cloud-cover frequency over the southern slope of the Himalayas will also be mentioned in Section 4.3 using the hourly data along 89°E.

So far, spatial and temporal cloud distributions have been discussed without taking account for snow-covered areas. It will be clarified here that snow-covered areas can be expected to be small enough to discuss the temporal variation of horizontal cloud distribution. Snow cover can be presumed relatively easily at 09 LST of the premonsoon period because of the reduced cloud cover (Fig. 2a), although discriminating between cloud cover and snow cover is generally difficult by VIS image alone. As shown in Fig. 2a, some areas around the peaks of Tanggula (Region A), Nyainqentanglha (Region B), and the Himalayas remain undefined as to whether they are cloud- or snow-covered. These doubtful areas are indicated by the arrows in Fig. 2a. In the monsoon period, almost the same areas are still suspected to be snow-covered, as shown in Fig. 2d, although the size of the areas is smaller than that in the premonsoon period. During both periods, these doubtful areas are small enough to warrant a debate over the relationship between the cloud cover and the topography. Although some areas near the peaks of the Himalayas may be covered by snow, most of the high-frequency area over the southern slope is presumed to be covered by clouds, because the frequency of high albedo \((a' \geq 0.40)\) has a prominent time evolution.

### 4.2 Daytime variation in the amount of cloud cover over the Tibetan Plateau

Figure 4 shows the number of grid points classified into each range of cloud-cover frequency in the area of elevation higher than 3,000 m a.s.l. in the analysis domain shown by Fig. 1b during (a) the premonsoon and (b) the monsoon periods. The number of classified grid points is an index of the amount of cloud cover over the plateau. About 90 percent of the grid points belong to the lowest frequency range (0–25%), i.e., little or no cloud cover over the plateau, during the forenoon (09–11 LST) in the premonsoon period (see Fig. 4a). After 11 LST (05 UTC), the amount of cloud cover rapidly increases, and the number of the grid points in the range of 0–25% becomes only about ten percent at 15 LST.

In contrast with the forenoon (09–11 LST) of the premonsoon period, the amount of cloud cover in the monsoon period continuously decreases through the forenoon (09–12 LST) and reaches the minimum at noon. This means that Fig. 2e shows the horizontal distribution of clouds at the minimum amount of cloud cover in the analysis hours (09–15 LST). The amount of cloud cover begins to increase after 12 LST, which is one hour later than in the premonsoon period. At 15 LST, few areas in the plateau remain in the lowest range (0–25%), and about a half of the grid points can be classified into the high-frequency ranges (50–100%). The amount of cloud cover at 15 LST in the monsoon period is higher than that in the premonsoon period.

### 4.3 Daytime variation of cloud distribution along 89°E

Figure 5 shows the north-south cross section of the hourly cloud-cover frequency along the
Fig. 2. Horizontal distribution of cloud-cover frequency in the premonsoon period (a), (b), (c) and in the monsoon period (d), (e), (f) at 09 LST, 12 LST, and 15 LST, respectively. All contours of altitude shown in Fig. 1b are drawn with a solid line. The areas indicated by arrows "\(" in (a) are expected to be snow-covered in the premonsoon period. In the monsoon period, although the snow-covered areas shrink to some degree, their location remains the same.

Fig. 3. (a) Topography and cloud distributions (b) at 09 LST and (c) at 15 LST during the monsoon period in the meso-scale domain (89.5°–93.5°E, 28.0°–33.0°N). These three figures are close-ups of Fig. 1b, Fig. 2d, and Fig. 2f, respectively. The characters “A,” “N,” and “L” in (a) indicate the locations of Amdo, Naqu, and Lhasa, respectively.

Fig. 4. The number of grid points classified into each range of cloud-cover frequency in the area over 3,000 m a.s.l. in the analysis domain shown in Fig. 1b during (a) the premonsoon and (b) the monsoon periods. The total number of grid points is 28,866.
89°E line averaged by ten grid points (0.5 degree width) during: (a) the premonsoon, and (b) the monsoon periods. A cross section of the topography is shown in the lower panel of Fig. 5, which has large undulation along the north-south direction (see Chapter 2). A peak of cloud-cover frequency around 34°N is expected to be covered with snow. For this reason, cloud activity around 34°N will not be discussed.

Through the forenoon (09–12 LST) of the premonsoon period (Fig. 5a), clouds are seldom observed over the plateau. During the monsoon period (Fig. 5b), on the other hand, clouds are frequently observed around 29.5°N, which is one of the major mountain ranges in the Tibetan Plateau. On the other hand, the cloud-cover frequency is quite low at a major valley around 29.2°N, which is Region C (Yarlung-Zangbo River). Furthermore, in the valley around 31.8°N, Region D, cloud-cover frequency is relatively low compared with that in surrounding mountain regions.

Over the southern slope of the Himalayas, cloud-cover frequency keeps increasing from 09 LST to 15 LST, and clouds are observed more frequently over the southern slope than over the plateau at 15 LST in both periods. Al-
though the temporal tendency of the amount of cloud cover is almost the same during both periods over the southern slope, a larger amount of cloud cover is always observed in the monsoon period than in the premonsoon period during daytime.

Over the Hindustan Plain (south from about 26.5°N), cloud-cover frequency is high in the morning of the monsoon period, decreasing through daytime. This tendency is opposite to that over the southern slope of the Himalayas, and it can be seen that clouds over the Hindustan Plain in the morning move over to the southern slope of the Himalayas in the afternoon.

4.4 Daytime variation of cloud-top temperature along 89°E

Figure 6 shows the north-south cross sections of the hourly cloud-top temperature along the 89°E line averaged by ten grid points. Dark-shading, light-shading, and clear areas indicate cloud-cover frequencies of over 40%, between 25 and 40%, and less than 25%, respectively. Clouds shown in the clear areas will not be discussed here because of their reduced statistical reliability. Table 2 shows the approximate relationship between air temperature and altitude obtained from NCEP/NCAR reanalysis data, and cloud-top elevation can be roughly estimated.

Figure 6 shows a difference in cloud-top temperature between over the southern slope of the Himalayas and, over the plateau in the afternoon during both periods. Cloud-top temperature is also quite different between the forenoon and afternoon during the monsoon period over the plateau. These contrasts can be identified by the threshold of 250 K defined in Section 3.5.
In Fig. 6, high-level clouds can be found over the plateau in the afternoon when the amount of cloud cover increases during both periods, as mentioned previously (see Fig. 5). The elevation of the cloud tops in the monsoon period is higher than that in the premonsoon period, since cloud-top temperature is over 230 K (less than 11,200 m a.s.l.) in the premonsoon period, while it is about 230 K (12,400 m a.s.l.) in the monsoon period. Cloud-top elevation grows in the afternoon during the monsoon period, although the time variation of cloud-top elevation is unclear in the premonsoon period.

Low-level clouds are observed around 29.5°N in the morning of the monsoon period, as shown in Fig. 6b, and this cloud-top temperature is about 260 K (about 7,900 m a.s.l.). These low-level clouds in Fig. 6b correspond to the high cloud-cover frequency shown in Fig. 5b.

Figure 6 shows that low-level clouds whose cloud-top temperature is about 260 K can be observed over the southern slope of the Himalayas, where cloud-cover frequency increases through the daytime during both periods, as mentioned previously (see Fig. 5). Cloud-top temperature of 260 K approximately corresponds to elevations of 6,800 m a.s.l. in the premonsoon period, and 7,900 m a.s.l. in the monsoon period.

A prominent contrast of cloud-top temperature can be found in the afternoon of the monsoon period between the southern slope of the Himalayas and the Hindustan Plain (south from about 26.5°N), where the ground surface is near sea level. High-level clouds are always observed over the Hindustan Plain in contrast with low-level clouds over the southern slope. This suggests that morning clouds over the Hindustan Plain are independent from low-level clouds appearing over the southern slope of the Himalayas in the afternoon.

4.5 Horizontal distribution of cloud-top temperature

Figure 7 shows the horizontal distribution of the mean cloud-top temperature (a) at 09 LST and (b) at 15 LST during the monsoon period. The areas with a small sample number of clouds, i.e., where cloud-cover frequency is under 25% in Fig. 7a, and under 40% in Fig. 7b, were blacked out because the mean temperature was without meaning.
Figure 7a shows that low-level clouds cover the Tibetan Plateau during the monsoon period, except in the valley region around the Yarlung-Zangbo River (Region C) between 89°E and 92°E. Figure 7b shows the cloud activities corresponding to the major topography in the plateau; namely, high-level clouds distribute along major mountain ridges, but clouds are seldom observed along major valleys. A clear border of cloud-top temperature can be observed along the peaks of the Himalayas in Fig. 7b. The high-level clouds are over the plateau, and the low-level clouds are over the southern slope of the Himalayas. Over the Hindustan Plain, high-level clouds were observed at 09 LST (Fig. 7a), and also at 15 LST (Fig. 7b).

5. Discussion

In the morning of the Tibetan Plateau, as mentioned in Chapter 4, less cloud cover was observed during the premonsoon period, and low-level clouds (i.e., low cloud-top elevation) were observed during the monsoon period. In the afternoon, on the other hand, high-level clouds were observed during both periods. It is well known that convective activity over the plateau is minimum at 09 LST (03 UTC), and maximum at 18 LST (12 UTC) through the analysis of the Ic (Index of Convection) of Murakami (1983) and Yanai and Li (1994). The results obtained in this study agree with those of the last two studies.

Convective activity was discussed in their studies without noting differences in cloud-top elevation and cloud-cover frequency, although the Ic includes these two elements. In our study, these two are separately analyzed. The cloud-cover frequency of high-level clouds increased over the plateau in the afternoon during both periods. Cloud-cover frequency has a similar tendency in both periods, but cloud-top elevation behaves differently; namely, cloud-top elevation in the monsoon period increases in the afternoon (Fig. 6b), while, cloud growth is more restricted at the lower level in the premonsoon period than that during the monsoon period (Fig. 6a). These two results lead the growth of the Ic in the afternoon in both periods. However, the ratio of contributions of the two elements is different. The growth of the cloud-cover frequency of high-level clouds is the primary contributor to the growth of Ic during the premonsoon period. During the monsoon period, on the other hand, both elements contribute to the growth of the Ic.

As mentioned in Chapter 4, high-level clouds distribute in the afternoon during the premonsoon and monsoon periods, corresponding to the major topography of the Tibetan Plateau, whose valley width is about 100–300 km. High-level clouds are frequently observed over major mountains, but fewer clouds are observed over major valleys. This distribution of high-level clouds corresponding to the major topography has already been reported through the analysis of GMS IR image of September 1997 by Kuwagata et al. (2001). With a simple two-dimensional numerical experiment, they found that the width of the major valleys (100–300 km) was suitable for moisture transport and cloud generation by thermally induced local circulation over the Tibetan Plateau. However, the relationship between the meso-scale (less than 100 km) distributions of clouds and the topography has not been discussed. In this study, meso-scale cloud distributions were investigated around Amdo and Naqu (BOX I of Fig. 3a) and around Lhasa (BOX II in Fig. 3a) during the monsoon period, and Fig. 3 shows that the cloud distribution indicates good correspondence to the topography in the BOX II region but only limited correspondence in the BOX I region.

This regional difference of meso-scale cloud distribution can be attributed to two factors. One is the valley depth, and the other is the east-west directional moisture advection. First, concerning valley depth, it should be mentioned that Lhasa is located at the bottom of a 1,400 m valley with a 40 km width. Amdo and Naqu, on the other hand, are located in valley bottoms with about half the depth, and twice the width of the valley around Lhasa. Figure 12 in Kuwagata et al. (2001) shows that precipitable water decreases in the daytime at the bottom of a valley with a width of less than 100 km, and that it decreases more prominently in a deeper valley. Their results explain the low cloud-cover frequency in the valley region around Lhasa at 15 LST (BOX II in Fig. 3c). Subsequently, the effect of moisture advection from the outside of the valleys by ambient wind is considered. Moisture can advect to the BOX I...
region along the major valley, which is Region D. The BOX II region, on the other hand, is surrounded by high-level mountains that seem to be obstacles to moisture advection.

The meridional distributions of high-level clouds in the afternoon over the Tibetan Plateau are different in the premonsoon and monsoon periods. During the premonsoon period, a large amount of high-level cloud cover distributes in the northern area of the plateau. On the other hand, the reverse is true during the monsoon period. The distribution of high-level clouds obtained in this study agrees with the past studies on the convective activity in the monsoon period. Ueno (1998) showed that a large amount of precipitation, which is estimated by using GMS IR images in the monsoon period, distributes in the southern area of the plateau. Ueno et al. (2001) also showed the same results with rain gages.

In the morning of the premonsoon period, fewer clouds were observed over the plateau. During the monsoon period, on the other hand, low-level clouds were observed in the southeast area of the plateau. The importance of the effect of low-level clouds on atmospheric heating as they release latent heat is uncertain because there is no evidence of any significant precipitation. However, low-level clouds affect the atmosphere through the radiation process. Daytime clouds suppress the surface heat flux, so the growth of a mixed layer is retarded and the thermally induced local circulation is weakened. Through these processes, low-level clouds in the morning of the monsoon period can modify the spatial and temporal distribution of daytime convective activity over the Tibetan Plateau. As mentioned in Section 4.2, the starting time of increasing the cloud in the monsoon period is one hour later than that of the premonsoon period (Fig. 4). This delay might be caused by low-level clouds in the morning during the monsoon period.

To clarify the origin of the low-level clouds, cloud distribution during the previous night should be investigated. Visible images, however, are available only for daytime clouds; in addition, there are several drawbacks to use infrared images for the detection of low-level clouds. Data obtained by radar and rain gages will be available, as well as TRMM PR data, if low-level clouds are accompanied by precipitation.

Low-level clouds are observed over the southern slope of the Himalayas during the premonsoon and monsoon periods. This fact implies that the forcing of southerly warm and wet wind ascending on the southern slope generates these low-level clouds, which produce a considerable amount of rainfall. The exact amount of rainfall cannot be determined by ground base observation because the topography is too complex. The large estimation error for precipitation over this area makes it difficult to estimate the magnitude of the heat source over the Tibetan Plateau and surroundings and to clarify the water vapor transport to the plateau beyond the Himalayas. The hourly evolution of the low-level clouds obtained in this study may help the temporal and spatial interpolation of precipitation data obtained by TRMM PR and rain gages. It will also help to verify clouds and precipitation estimated by numerical models.

According to Fig. 12 of Ohsawa et al. (2001), the convective activity over the Hindustan Plain reaches the daily maximum in the morning during the monsoon period. This study supports the daytime part of their result, and furthermore, new facts were clarified by analyses of cloud-cover frequency and cloud-top elevation. The cloud-top elevation over the Hindustan Plain is always high from 09 LST to 15 LST (Fig. 6b); however, the cloud-cover frequency keeps decreasing (Fig. 5b). These results in this study lead the convective activity to the daytime decrease.

Murakami (1983) and Yanai and Li (1994) reported that there was weak convection over the Brahmaputra Valley (see Fig. 1) at 18 LST when the convective activity over the Tibetan Plateau was at its maximum. Figure 7b also shows a similar tendency although it was obtained at 15 LST. As shown in this figure, clouds covered the Brahmaputra Valley with the frequency less than 40%; therefore, this area was blacked out. While the previous two studies just pointed out the weakness of the convective activity in this region, this study clarified that the area is not frequently covered by either deep convective or low-level clouds. As mentioned above, the southern slope of the Himalayas also seems to be a weak convection area. Although both convective activities at the southern slope of the Himalayas and the Brah-
maputra Valley are weak, these two regions differ considerably in cloud-cover frequency; namely, the Brahmaputra Valley has a low cloud-cover frequency, but the southern slope of the Himalayas is almost always covered by low-level clouds.

6. Conclusion

Daytime cloud activities over the Tibetan Plateau and its surrounding areas were investigated focusing on their relationships to topography, using hourly GMS visible and infrared images (09–15 LST) in order to grasp the cloud horizontal distribution and to estimate cloud-top elevation, respectively. The results are concluded as follows:

1) Daytime variation of cloud activity is observed over the Tibetan Plateau during the premonsoon and the monsoon period, as discussed earlier (Murakami 1983; Yanai and Li 1994; Fujinami and Yasunari 2001). In both periods, cloud activity is weak at 09 LST (03 UTC) and strong at 15 LST (09 UTC). In the premonsoon period, the amount of high-level cloud cover (i.e., high cloud-top elevation) increases through the afternoon, although cloud growth is restricted at the lower level than it is during the monsoon period. In the monsoon period, on the other hand, both factors, i.e., cloud-top elevation and the amount of cloud cover, increases through the afternoon;

2) In the afternoon of the premonsoon period, a large amount of high-level cloud cover is observable over the northern area of the Tibetan Plateau. On the other hand, the opposite is true in the afternoon of the monsoon period;

3) Afternoon high-level clouds are distributed according to the major topography (100–300 km) in the Tibetan Plateau during the premonsoon and monsoon periods, as shown in Ueno (1998) and Kuwagata et al. (2001), although their results are limited to the monsoon period. However, the contrast in cloud activities in the mountain and valley regions over meso-scale topography (less than 100 km) is not always clear. The horizontal distribution of high-level clouds may be caused by thermally induced local circulation, as discussed in Kuwagata et al. (2001);

4) In the morning, fewer clouds are found over the plateau in the premonsoon period, while low-level clouds (i.e., low cloud-top elevation) are observed around the southeastern part of the plateau in the monsoon period. These low-level clouds may suppress surface heat flux and delay the development of the mixed layer and thermally induced local circulation. As a result, the diurnal cycle of the cloud activity may be modified. The starting time of cloud activity in the monsoon period is one hour later than that in the premonsoon period. One of the reasons of this delay is the low-level clouds in the morning;

5) Across the peaks of the Himalayas, different kinds of cloud activities are observed during both periods. One is the high-level cloud cover over the Tibetan Plateau, and the other is low-level cloud cover over the southern slope of the Himalayas; and,

6) Convection is weak over the Brahmaputra Valley at 15 LST, as pointed out in Murakami (1983) and Yanai and Li (1994), although they showed results at 18 LST. This study clarified the cloud activities over the southern slope of the Himalayas, as well as over the Brahmaputra Valley. It is common that high-level clouds rarely cover both regions in the afternoon during the monsoon period. The amount of cloud cover, however, is largely different in the two regions: namely, there are fewer clouds over the Brahmaputra Valley, and a considerable amount of low-level cloud cover over the southern slope of the Himalayas.

The above-mentioned cloud activities cannot be discussed in detail from the point of view of precipitation activities alone, although precipitation information is necessary for any discussion of the heat source over the Tibetan Plateau. According to the rain gage observations in the past studies, it is almost certain that low-level clouds over the southern slope of the Himalayas accompany precipitation. However, problems remain on spatial and temporal distributions of precipitation, especially from low-level clouds over the southern slope because of the steep and complex terrain. It is also difficult to estimate the amount of precipitation in the high-level clouds in the premonsoon period and in the low-level clouds in the morning of the
monsoon period. Analysis of TRMM PR data and the numerical experiment are expected to clarify these precipitation activities, and the findings of the present study will assist with future studies.

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