Mesoscale Characteristics and Structures of Stratiform Precipitation on the Tibetan Plateau

By Shuji Shimizu

Earth Observation Research Center, National Space Development Agency of Japan, Tokyo, Japan

Ken’ichi Ueno

School of Environmental Science, The University of Shiga Prefecture, Shiga, Japan

Hideyuki Fujii1

Department of Civil and Environment Engineering, Nagaoka University of Technology, Nagaoka, Japan

Hiroyuki Yamada2

Department of Earth and Planetary Science, Hokkaido University, Sapporo, Japan

Ryuichi Shirooka2

Department of Rural Development, Hokkaido National Agricultural Experiment Station, Sapporo, Japan

and

Liping Liu3

Lanzhou Institute of Plateau Atmospheric Physics of the Chinese Academy of Sciences, Lanzhou, PRC

(Manuscript received 7 February 2000, in revised form 30 October 2000)

Abstract

During the GAME-Tibet Intensive Observation Period (IOP), the precipitation radar (PR) of the Tropical Rainfall Measuring Mission (TRMM) satellite detected a diurnal cycle of rainfall in Tibet. Much rainfall was brought both by convection in the daytime and by stratiform precipitation over a wide rain area in the evening and night.

Two case studies were conducted to clarify the structure of stratiform rainfall in the nighttime. In Case 1 (7 and 8 July 1998), stratiform precipitation was observed in the evening and night. On 7 July, a synoptic convergence area developed in the southern part of the Plateau in the evening. Southwesterly wind dominated above the 6 km ASL, but the wind direction below 6 km ASL was variable during the rainfall. When the mesoscale convergence strengthened, the rainfall amount became large. On 8 July, a convergence zone between southwesterly wind and northerly wind was detected and passed over the radar site in the evening. A sudden wind direction change from westerly to northwesterly was observed below 8 km ASL from the vertical profiles at the radar site. The boundary between the two wind directions may correspond to the cold frontal surface. However, the precipitation with the frontal passage was stratiform and had a low echo top. The variation of rainfall on the two days was consistent with the diurnal variation revealed by TRMM PR.
In Case 2 (1 and 2 August 1998), there was no remarkable disturbance in the synoptic field, but much rainfall (exceeding 4 mm/h) was observed in the midnight. A 90 km-diameter stratiform echo stayed over the radar site for seven hours. Below 6 km ASL, the wind direction varied from northerly to northeasterly, then to easterly. When northeasterly wind dominated, the convergence in the lower layer strengthened and stratiform precipitation was intensified.

Mesoscale convergence of moist air in the lower layer effectively contributes to development and maintenance of stratiform rainfall.

1. Introduction

It is important to understand the rainfall characteristics on the Tibetan Plateau because the convection, rainfall and the associated release of latent heat exceeding 4,000 m in altitude influences variations of Asian monsoons. However, there is little observational data of the rainfall because of the severe weather conditions of the Tibetan Plateau. The Global Energy and Water Cycle Experiment (GEWEX) Asian Monsoon Experiment (GAME)-Tibet project was conducted to clarify the interactions between the land surface and the atmosphere over the Tibetan Plateau in the context of the Asian monsoon system. The GAME-Tibet radar and precipitation group conducted field observations using an X-band Doppler radar of the National Space Development Agency of Japan (NASDA), rain gauges, a microwave radiometer, and some observational instruments near Naqu in September 1997 for the Preliminary Observation Period (POP) and from May to September 1998 for the Intensive Observation Period (IOP) (Koike et al. 1999). The observations sought to:

- Clarify the evolution and mesoscale structure of the rainfall system on the Tibetan Plateau,
- Construct the precipitation distribution and areal rainfall amount, and
- Validate the Tropical Rainfall Measuring Mission (TRMM) on the ground.

The TRMM satellite, launched in November 1997, carries the world’s first satellite-borne precipitation radar (PR).

The area near Naqu was observed by a radar during the Qinghai-Xizang Plateau Meteorological Experiment (QXPMEX) in 1979 (Zhang et al. 1988). The radar analyses in QXPMEX show high echo top exceeding 13 km above the ground and small horizontal scale of the radar echoes. However, there are few studies or reports of the mesoscale structure and detailed rainfall processes on the Tibetan Plateau. An X-band Doppler radar is one of the most powerful instruments for detecting the mesoscale structures and the dynamics of a precipitation system. Yamada et al. (2000) presented a case study on the characteristics of the convective cloud system revealed by the X-band Doppler radar in the POP. They referred to diurnal variations and reported the nighttime rainfall. In the IOP, continuous stratiform rainfall was frequently observed in the Naqu area. Shimizu et al. (1999) presented a direct comparison between the TRMM PR Z-factor and the reflectivity of the Tibet radar for ground validation of TRMM using the stratiform rain case on 1 August 1998 in the IOP. Because stratiform precipitation has large rain areas and continues for a long time, the total amount of stratiform precipitation is large. Thus it is important to clarify the characteristics and structures of the stratiform precipitation. However, there are no studies about detailed structures of stratiform precipitation. In this paper we will focus on the detailed characteristics of stratiform precipitation. In Section 2, we will present the data set and methods of the analyses. Characteristics and an overview of precipitation on the Tibetan Plateau during the IOP are described in Section 3. We analyze two cases of the stratiform precipitation in the IOP and describe the synoptic fields and mesoscale structures of the stratiform precipitation in two case studies in Section 4. The principal results and discussions of the study are summarized in Section 5.

2. Data

Figure 1 shows a map of the instruments in the GAME-Tibet mesoscale observation area. The

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E-mail: shimizu@ecrc.nasda.go.jp

1 Present affiliation: Japan Science and Technology Corporation, Core Research for Evolutional Science and Technology
2 Present affiliation: Frontier Observational Research System for Global Change
3 Present affiliation: Chinese Academy of Meteorological Sciences
Fig. 1. Map of the mesoscale observation area for GAME-Tibet. Circles indicate the observation area of the Doppler radar (Small (64 km), Doppler mode; Large (128 km), Intensity mode). The rectangle indicates the sampling area of TRMM PR data (see Fig. 4).

Fig. 2. Photograph of NASA X-band Doppler radar for TRMM ground validation.
NASDA X-band Doppler radar was set up on a hill 15 km southwest from Naqu (31.4°N, 91.9°E; “Radar” in Fig. 1), Tibetan Plateau. This site is 4,548 m above sea level (ASL). A photograph and specifications of the radar system are presented in Fig. 2 and Table 1. The transmitting frequency is 9,410 MHz (X-band, 3.2 cm wavelength), and the two observation modes, Doppler mode and intensity mode, depend on the repetition frequency. The maximum detection range is 64 km (radius), and the range resolution is 125 m in the Doppler mode. In the intensity mode, the maximum detection range is 128 km (radius), and the range resolution is 250 m.

Radar observations were conducted from 30 August to 10 September 1997 in the POP and 27 May to 19 September 1998 in the IOP. The radar was operated continuously, and a 10-minute operation series was repeated during the POP and IOP. The 10-minute operation was a volume scan with 10-elevation Plan Position Indicator (PPI) scans in Doppler mode, three PPI scans in intensity mode, and Range Height Indicator (RHI) scans (Table 2). When the TRMM satellite approached the radar site, vertical cross sections normal and parallel to the orbit were obtained in order to directly compare the reflectivities of the PR and the NASA radar. Because the operation series did not contain the vertical pointing scan, a vertical profile of the reflectivity was made by averaging PPI reflectivity data at an elevation angle of 20°.

We adopted the Velocity Azimuth Display (VAD) method in this paper in order to obtain a vertical profile of the horizontal wind from Doppler velocity data (Browning and Wexler 1968). We also adopt the Extended VAD (EVAD) method (Srivastava et al. 1986; Tsukobu and Wakahama 1988) in order to obtain the vertical profiles of horizontal divergence. We used an elevation angle of 20° for the VAD method and elevation angles of 20° and 10° for the EVAD method. The circle for calculating the divergence is 11.2 km in diameter at 1.5 km above ground level. Air temperature, wind speed, and wind direction near the surface were measured at the radar site every minute during the observation period. Wind data of a Portable Automated Mesonet III (PAM III) at MS3478 and an Automatic Weather Station (AWS) at MS3608 were also used. MS3478 (MS3608) is 60 km north-northwest (30 km southwest) of the radar site. Fourteen rain gauges were placed in the mesoscale area.

TRMM PR observes the horizontal and vertical structures of rain wherever it occurs from 350 km above the Earth’s surface between the latitude of 36°N and 36°S. It operates at 13.8 GHz, with a 220 km swath and horizontal and vertical resolutions of 4.3 km and 250 m at nadir. The 1C21 product of TRMM has a Z-factor (radar reflectivity factor) parameter. This parameter can be directly compared with a ground-based radar. The 2A23 products are storm height and classification of convective or stratiform rain (Awaka et al. 1996). The storm height is the top of the Z-factor exceeding minimum echo flag in the 1C21. The 2A25 product has three-dimensional rain-rate data. This product also has a Z-factor parameter considered for rain attenuation correction (Iguchi et al. 1996).

Rawinsondes were launched from the Planetary Boundary Layer (PBL) tower site near Amdo, which is about 90 km north-northwest from Naqu, in order to acquire information on the upper air. The observation period was from 2 June to 21 August 1998. Eight rawinsondes per day (every three hours) were launched during the special observa-

| Table 1. Principal specifications of NASDA X-band Doppler radar. |
|------------------------|------------------|
| Frequency              | 9,410 MHz        |
| Peak Power             | 40 kW            |
| Beam Width             | 1.3°             |
| Pulse Width            | 0.45 ms/0.90 ms  |
| Repetition Frequency   | 2000 Hz/1000 Hz  |
| Maximum Range          | 64 km/128 km     |
| Range Resolution       | 125 m/250 m      |
| Velocity Resolution    | 12.5 cm/s        |
| Nyquist Velocity       | ±1.59 m/s        |

| Table 2. Series of observation cycles of the NASDA radar on GAME-Tibet. |
|------------------------|------------------|
| Normal mode            | Volume scan – PPI 10 elevations (Doppler mode) |
|                        | 1.5, 2.5, 3.5, 5.0, 6.5, 8.0, 10.0, 12.5, 15.0, 20.0 |
| Areal rainfall accumulation – PPI 3 elevations (Intensity mode) |
|                        | 0.7, 1.5, 2.5 |
| Vertical structure     | - RHI 3 azimuths (Doppler mode, Automatic) |
|                        | - 45.2 - Hydrological station (SPOS, Raingauges, etc.) |
|                        | - 213.7 - South PAM |
|                        | - 295.4 - Zuni (Rain gauge) |
|                        | - RHI optional azimuths (Doppler mode, Manual) |
| TRMM validation mode   | Volume scan – PPI 10 elevations (Doppler mode) |
|                        | 1.5, 2.5, 3.5, 5.0, 6.5, 8.0, 10.0, 12.5, 15.0, 20.0 |
| Vertical structure for TRMM |
|                        | RHI 4 azimuths (Intensity mode, Manual) |
|                        | Along and normal to TRMM orbit (4 azimuths) |
tion period in June. Three or five rawinsondes per day were launched in the other period. The data at 0000 UTC and 1200 UTC were used for the time-series analysis in this paper.

This paper used Japan Meteorological Agency (JMA) global objective analysis (GANAL) data and Geostationary Meteorological Satellite (GMS) Infrared data to investigate the synoptic field of winds, height, and precipitable water. The GMS data were received and processed by the Institute of Industrial Science, University of Tokyo, and provided by Kochi University.

3. Characteristics of Precipitation during the IOP

Before we describe the individual rainfall cases, we will describe the characteristics of the precipitation in the mesoscale observation area of GAME-Tibet during the IOP. Figure 3 shows the temporal variation of daily radar reflectivity during the IOP obtained by Yamada et al. (1999). On 13 June 1998, the echo-top height abruptly increased. Strong convective activity with a high echo-top height of 10 dBZ more than 15 km ASL developed every day. This result suggests that the Tibetan monsoon season started on 13 July 1998. The echo-top height and echo area of reflectivity suddenly fell on 9 July. Few echoes exceeded 30 dBZ between 9 and 19 July. The echo-top height increased and the echo area broadened again on 19 July and continued until 2 September. The echo-top height of 10 dBZ after 18 July was the same as that before 9 July. However, the echo-top heights of 30 dBZ and echo area after 18 July were lower than before 9 July. This suggests that convective activities on the Plateau after 18 July were weaker than before 9 July. The height and area rose again in the middle of September. The variations during the IOP are consistent with those of daily rainfall measured in the mesoscale observation area and precipitable water revealed by sounding data (not shown).

The TRMM satellite has a non-sun-synchronous orbit, so we can produce the diurnal cycle of rainfall from the TRMM data. Area-averaged rain rate, averaged storm height, proportion of convective rain to all rain in the rectangular area, and the rain area to the rectangular area in Fig. 1 were calculated from the TRMM PR data. This rectangular area almost covers the overlapping area of the Naqu hydrological basin and Doppler radar coverage. Figure 4 shows three-hourly variations of each parameter that were composed from all data during the IOP. We collected 87 cases during the IOP. The area-averaged rainfall rate near the surface has a peak between 1200 and 1500 UTC (Local time = UTC + 6) (Fig. 4a). The maximum storm height and proportion of convective rain occurred between 0900 and 1200 UTC (Figs. 4b and 4c).

Fig. 3. Time series of a) the echo-top height b) and the echo area from 27 May to 19 September 1998. Light (dark) gray columns show the daily maximum of a) the echo-top height and b) the echo area for 10 dBZ (30 dBZ) in the Doppler radar observation area. The white arrow indicates 13 June and shaded area indicates the monsoon period of 1998 on the Tibetan period. An “x” means that no data was obtained. [From Yamada et al. (1999).]
c). These parameters are low after 1200 UTC. A peak proportion of rain area existed between 1200 and 1500 UTC, and the value was also high between 1500 and 1800 (Fig. 4d). These results indicate that precipitation with a high storm height developed in the afternoon (0900 to 1200 UTC). However, the rain area was not large. In contrast, large stratiform precipitation developed in the evening and night (1200 to 1800 UTC), and the largest amount of rainfall was from 1200 to 1500 UTC in the Naqu area. Diurnal variation is a basic characteristic of the precipitation in the mesoscale area of the GAME-Tibet. In the next section, two case studies of the stratiform precipitation in the evening and night will be shown based on the results from TRMM PR data.

4. Structures of the stratiform precipitation from the case studies

In order to clarify structures of stratiform rainfall on the Tibetan Plateau, we chose a continuous rainfall from 7 to 8 July 1998 (Case 1) and from 1 to 2 August 1998 (Case 2) for case studies. The results of the synoptic analyses for environmental fields and mesoscale variations of each case are described in this section.

4.1 Case 1 (7 and 8 July 1998)

a. Synoptic analyses

We will describe the precipitation on 7 and 8 July 1998 as Case 1. The total rain amount during the two days was 30.4 mm. Figure 5 shows the daily means of wind and height at 500 hPa (solid contour) and precipitable water above 600 hPa (dashed contour) in the Tibetan Plateau, using JMA GANAL data. The rectangle indicates the mesoscale observation area of GAME-Tibet, and the asterisk (*) indicates the radar site (Fig. 1). The shaded area indicates the precipitable water exceeding 14 mm. A depression appeared in the middle of the Tibetan Plateau on 6 July 1998. Warm and moist advection with southerly wind exists on the east of the depression. The depression became strong, and the area moved east and reached the northeast of the radar site on 8 July 1998 (Fig. 5c). A trough extended from the depression toward the southwest. It existed over the mesoscale observation area and reached the Himalayas. An anticyclone developed west of the cyclone and brought northerly wind with dry air to the mesoscale observation area. Meanwhile, southwesterly wind brought wet air from the south of Tibet. A convergence line can be drawn between the two air masses (Fig. 5c). A sharp gradient of precipitable water existed with the convergence line.
Fig. 5. Time series of daily-averaged JMA global objective analysis (GANAL) of 500 hPa wind (arrows, m s⁻¹), precipitable water above 600 hPa (dashed contour) and 500 hPa height (thick solid contour) from 6 to 8 July 1998. Thin solid contour indicates altitude every 1500 m ASL. The shaded area indicates precipitable water exceeding 14 mm. Thick line indicates the convergence line between northerly wind and southwesterly wind.
The six-hourly wind and divergence fields at 500 hPa on 7 and 8 July 1998 are shown in Fig. 6. Strong convergence exceeding \(0.8 \times 10^{-5}\) s\(^{-1}\) (divergence is less than \(-0.8 \times 10^{-5}\) s\(^{-1}\)) is shown in gray. At 0000 UTC on 7 July 1998, a convergence area lay from 33°N, 96°E to 29°N, 84°E. The western part of the convergence area strengthened at 0600 UTC 7. The area expanded to a large area of the eastern Plateau at 1200 UTC 7 (Fig. 6c), then there were very few convergence areas at 1800 UTC (Fig. 6d). A convergence area also appeared at 0000 UTC on 8 July (Fig. 6e). This area moved toward the east and passed over the radar site (Figs. 6f and 6g). Before the passage of the area, southwesterly wind dominated over the radar site; northwesterly wind dominated after the passage.

Figure 7 shows time-height cross sections of horizontal wind, equivalent potential temperature (\(\theta e\)), and relative humidity using twelve-hourly sounding data from 1200 UTC 8 July to 1200 UTC 9 July 1998. Air with high relative humidity (exceeding 80%) existed below 10.0 km ASL from 0000 UTC 7 July to 0000 UTC 8 July. The change of the \(\theta e\) profile shows a clear diurnal cycle, that is, \(\theta e\) was low in the morning (0000 UTC) and became high in the evening (1200 UTC) below 7.0 km ASL. However, at 1200 UTC on 8 July the relative humidity became less than 80% below 6.5 km ASL, and at 0000 UTC on 9 July it became less than 80% below 8.5 km ASL. The \(\theta e\) value abruptly decreased from 354 K at 1200 UTC on 8 July to 336 K at 0000 UTC on 9 July at 6.5 km ASL. There were convectively unstable conditions below 6.5 km ASL and stable conditions above the layer at 0000 UTC on 9 July. An especially strong gradient of \(\theta e\) existed at
8.0 km ASL. The wind direction was southwesterly above 8.0 km ASL and northwesterly below 8.0 km ASL. The variations of the wind profiles and relative humidity were consistent with the synoptic fields of Figs. 5 and 6. The vertical structure was consistent with the \( \theta_e \) profile change with a cold frontal passage of Hobbs et al. (1980).

Figure 8 shows brightness temperature images acquired by the GMS infrared instrument every three hours from 7 to 8 July 1998. The rectangle and asterisk are the same as in Fig. 5. A cloud band extending from northeast to southwest appeared near the radar site at 0600 UTC on 7 July. Some small cloud clusters developed and expanded north and south of the radar site at 0900 and 1200 UTC on 7 July. These clouds merged at 1500 UTC on 7 July, then the clouds weakened. On 8 July 1998, the cloud evolution was very similar to that of 7 July, that is, a cloud band existed at 0600 UTC and small cloud clusters appeared and merged from 0900 UTC to 1500 UTC. This variation of clouds corresponded to the diurnal variation of rainfall in Fig. 4. However, the synoptic fields revealed by GANAL differed between the two days, that is, convergence area developed in the center of the Plateau in the evening of 7 July and convergence zone moved eastward over the Plateau on 8 July.

b. Mesoscale structures

Figure 9 shows the time sequence of vertical profiles of radar reflectivity, horizontal wind, and horizontal divergence revealed by the VAD method and EVAD method, and hourly rainfall at the Naqu hydrological station ("NaquHy" in Fig. 1) from 0600 UTC on 7 July to 0600 UTC on 8 July.

Strong rain fell on the radar site for two hours from 1300 UTC on 7 July 1998 (Fig. 9a). The rain rate exceeded 3 mm/h and the echo top exceeded 12 km ASL. Figure 10 shows a time series (20-minute intervals) of the horizontal images of radar reflectivity at 5.5 km ASL (1.0 km from the ground). A broad stratiform echo existed northwest of the radar site. The stratiform echo moved eastward and covered the radar site. A small convective echo existed 15 km southwest from the radar site. Figure 11 shows the vertical images of the radar reflectivity along the lines a, b and c from 1247 UTC to 1249 UTC on 7 July. The echo that existed on the northwest side has a clear bright band at 5.5 km ASL and 8.0 km ASL echo-top height (Fig. 11b). Convective echoes existed 8.0 km from the radar site and had a 13.0 km ASL echo-
Fig. 8. Three hourly GMS/IR brightness temperature from 0000 UTC 7 July to 2100 UTC 8 July 1998. The rectangle indicates the mesoscale observation area of GAME-Tibet, and the asterisk (*) indicates the radar site.
Fig. 9. Time-height cross section of the vertical profiles of (a) radar reflectivity, (b) VAD horizontal wind (arrows, m s$^{-1}$) and divergence (colored contours, $\times 10^{-4}$ s$^{-1}$) profiles from the X-band Doppler radar and (c) hourly rainfall (mm/h) at Naqu Hydrological site ("NaquHy" in Fig. 1) from 0600 UTC 7 July to 0600 UTC 8 July 1998.
top height and strong reflectivity (more than 30 dBZ) (Fig. 11c). The convective echo also moved eastward and passed south of the radar site. This rain lasted until 0300 UTC on 8 July (Fig. 9c). A stratiform echo that had a clear bright band dominated until the disappearance of the rain (Fig. 9a). The echo top height of 10 dBZ was 8.0 km ASL. The bright band height was 5.5 km ASL and decreased to 5.2 km ASL at night. This variation corresponded to the variation of air temperature at the radar site in Fig. 12d.

Southwesterly wind dominated above 6.0 km ASL from 1200 UTC on 7 July to 0200 UTC on 8 July 1998. The winds fluctuated below 6.0 km ASL. Between 1200 UTC and 1500 UTC on 7 July, strong northerly or northeasterly wind existed below 5.5 km ASL. There was a strong vertical shear between northerly and southwesterly winds at 5.5 km ASL. After 1500 UTC, the wind in the lower layer changed to westerly, and the wind speed decreased. From 1900 to 2200 UTC, southerly wind dominated over the radar site. Westerly wind then dominated again from 2200 UTC to the end of the rainfall. This wind variation corresponded to the variation of the surface wind at the radar site (Fig. 12b). The wind variation was consistent with that of MS3608 except for a one-hour time lag (Fig. 12c). The eastward movement of the rainfall system caused this time lag.

Throughout this period, divergence mostly developed above and convergence below 6.0 km ASL. The peak of the rainfall was from 1300 to 1500 UTC, from 1800 to 1900 UTC, from 2000 to 2100 UTC, and from 2300 UTC 7 July and 0000 UTC
8 July. The peak time of the rainfall was consistent with the appearance of strong reflectivity and convergence below 6.0 km ASL (Fig. 9). Especially strong convergence existed from 1200 to 1500 UTC 7 July.

Figure 13 shows a time sequence of vertical profiles of radar reflectivity, horizontal wind and horizontal divergence, together with hourly rainfall at the Naqu hydrological station from 0600 UTC to 1800 UTC on 8 July. Rain began to fall from 0820 UTC and continued to 1620 UTC on 8 July. The rainfall of the period was weaker than that of 7 July (Fig. 9c). Stratiform precipitation with a clear bright band was observed during this period. The echo top height gradually decreased from 12.0 km ASL at 0800 UTC to 6 km UTC at 1620 UTC on 8 July. In the beginning of the period, southwesterly wind dominated in the whole layer. The wind gradually changed to westerly. The wind direction below 8.0 km ASL suddenly changed to northwesterly around 1300 UTC on 8 July. A boundary between westerly wind and northwesterly wind can be drawn (line A-A’ in Fig.13b). Convergence developed along line A-A’, then the profile abruptly changed to divergence. The temperature suddenly fell two degrees at 1255 UTC in Fig.13b. These wind shifts corresponded to a cold front passage over the radar site.

Figure 14 shows a time series of the horizontal images of radar reflectivity (10-minute intervals) from 1230 UTC on 8 July at 5.5 km ASL (1.0 km from the ground). There are large areas of reflectivity northeast and southwest of the radar site at 1230 UTC. Many small echoes existed in the large area. One of the echoes approached the radar site from the west and passed over the radar site at 1250 and 1300 UTC (Figs.14c and 14d). Figure 15 shows the vertical images of the radar reflectivity along the lines a, b and c in Fig.14c from 1257 UTC to 1259 UTC on 8 July. The small echo was not strong, and the echo top height was 7.5 km ASL (Fig.14b and 14c). It then moved southeastward and cannot be distinguished from surrounding echoes at 1320 UTC (Fig.14f). Stratiform echoes and northwesterly wind dominated until disappearance of precipitation at 1620 UTC on 8 July (Fig.13a).

The results of the analyses of Case 1 show that the variations of the rainfall on 7 and 8 July 1998 were consistent with the diurnal variation from the...
Fig. 12. Time variation of wind direction (dots), wind speed (line) at (a) MS3478, (b) Naqu radar site and (c) MS3608 and (d) temperature at Naqu radar site from 0600 UTC 7 July to 0600 UTC 9 July 1998.
Fig. 13. Same as Fig. 9 except for 0600 UTC to 1800 UTC 8 July 1998. Solid line shows the boundary between westerly wind and northwesterly wind (line A–A').
Fig. 14. Same as Fig. 10 except for 1230 UTC to 1320 UTC 8 July 1998.
TRMM PR (Fig. 4), although a cold frontal passage over the radar site was analyzed on 8 July. In the next subsection, we will describe a case study of stratiform precipitation in the midnight.

4.2 Case 2 (1 and 2 August 1998)

a. Synoptic analyses

The daily means of wind and height at 500 hPa (solid contour) and precipitable water above 600 hPa (dashed contour) on the Tibetan Plateau from 30 July to 1 August 1998 are shown in Fig. 16 using GANAL data. There were no remarkable disturbances on 30 and 31 July. On 1 August, a depression appeared on the east of the radar site. North-easterly wind dominated over the radar site. A high precipitable water area exceeding 14 mm existed from the western plateau to the south of the radar site on 30 July. It gradually expanded to the east side of the plateau.

Figure 17 shows the six-hourly wind and divergence field at 500 hPa on 1 August 1998. There were few convergence areas at 0000 UTC and 0600 UTC (Figs. 17a and 17b). At 1200 UTC, a strong convergence developed around 30°N, 80°E (Fig. 17c). A strong northerly wind blew in the area.

Another strong convergence area existed south of the radar site. This area corresponded to the boundary between westerly wind in the south and north-easterly wind around the radar site. At 1800 UTC, no convergence existed in the mesoscale observation area (Fig. 17d). This variation was similar to that on 7 July 1998 (Fig. 6). However, no rain fell on the radar site in the afternoon and evening, and rainfall exceeding 3 mm/h was observed in the midnight (Fig. 20c).

Figure 18 shows time-height cross sections of horizontal wind, equivalent potential temperature ($\theta_e$), and relative humidity using twelve-hourly sounding data from 1200 UTC on 30 July to 1200 UTC on 2 August 1998. $\theta_e$ below 10 km ASL had a clear diurnal variation, small in the night (0000 UTC) and large in the daytime (1200 UTC). There was moist air with high relative humidity (exceeding 80%) below 7.7 km ASL at 0000 UTC on 31 July. At 1200 UTC on 31 July, the relative humidity below 7.5 km ASL decreased to below 80%. At 0000 UTC and 1200 UTC on 1 August, the relative humidity below 9.5 km ASL exceeded 80%. The stratification was convectively unstable below 7.5 km ASL at 1200 UTC. Relative humidity then decreased to
Fig. 16. Same as Fig. 5 except for 30 July 1998 to 1 August 1998.
Fig. 17. Same as Fig. 6 except for 1 August 1998.
less than 80% below 7.5 km ASL at 0000 UTC on 2 August. The also decreased from 354 K at 1200 UTC on 1 August to 347 K at 0000 UTC on 2 August.

GMS/IR images every two hours from 1400 UTC on 1 August to 0000 UTC on 2 August are shown in Fig. 19. High clouds developed north and south of the radar site at 1400 UTC on 1 August. The north clouds moved to the south at 1600 UTC (Fig. 19b) and stayed just over the radar site until 2200 UTC (Figs. 19c, 19d and 19e). The cloud decayed at 0000 UTC on 2 August. We will next describe the results of detailed analyses of the stationary cloud over the radar site.

b. Mesoscale structures

Figure 20 shows a time sequence of vertical profiles of radar reflectivities, horizontal wind, and horizontal divergence obtained by the radar, and hourly rainfall at MS3478, the Naqu hydrological station and MS3608 from 0600 UTC on 1 August to 0600 UTC on 2 August. Rain began to fall on the radar site from 1530 UTC 1 and continued to 0130 UTC on 2 August. The total rain amount was 21.7 mm. Stratiform precipitation with a clear bright band was observed during this period. Especially strong reflectivity (more than 30 dBZ) at the bright band height was observed from 1900 UTC to 2100 UTC on 1 August. The bright band height was 5.3 km ASL during the rain. Rainfall exceeding 4 mm/h was observed during the two hours. The echo top height exceeded 9 km ASL before 1940 UTC and was 8.5 km ASL after 1940 UTC. Figure 21 shows a time series of horizontal maps of radar reflectivity at 5.5 km ASL every two hours from 1600 UTC on 1 August. A large radar echo existed north of the radar site at 1600 UTC. The radar echo gradually moved southward and approached the radar site. It covered the site at 1800 UTC (Figs. 21a and 21b). The echo diameter was 90 km. It then remained stationary, and high reflectivity exceeding 25 dBZ was maintained around the radar site at 2000 and 2200 (Figs. 21c and 21d). The echo disappeared over the radar site at 0200 UTC on 2 August. This echo variation corresponded well to the variation of the cloud in the GMS images (Fig. 19).

Easterly wind dominated above 6.5 km ASL until 1600 UTC on 1 August (Fig. 20b). The wind speed, however, was very low. From 1800 UTC to 2030 UTC on 1 August, the wind speed between 6.5 km ASL and 8.0 km ASL was nearly zero. After 2030 UTC, the wind changed to north-easterly above 6.5 km ASL. Below 6.5 km ASL, the wind direction changed in a short time. Weak easterly wind existed from 1520 to 1620 UTC. Strong northerly wind dominated from 1620 UTC to 1740 UTC below 5.5 km ASL. The wind direction sud-
Fig. 19. Two hourly GMS/IR brightness temperature from 1400 UTC 1 August to 0000 UTC 2 August 1998. The rectangle indicates the mesoscale observation area of GAME-Tibet and the asterisk (*) indicates the point of radar site.
Fig. 20. Same as Fig. 9 except for 0600 UTC 1 August to 0600 UTC 2 August 1998 and hourly rainfall at MS3478, Naqu and MS3608.
Fig. 21. Same as Fig. 13 except for 1600 UTC to 2200 UTC 1 August 1998.

ddenly changed to northeasterly, and the high wind speed continued until 2100 UTC. After 2100 UTC, the wind direction returned to easterly and wind speed decreased near the surface.

From 1700 UTC to 0200 UTC, convergence dominated below 5.5 km ASL, and divergence dominated above 5.5 km ASL. The convergence strengthened between 1700 UTC and 2100 UTC. This period corresponded to the period of strong rainfall and northerly or northeasterly wind. After 2100 UTC, the precipitation became weak and convergence near the surface became weak.

Figure 22 shows the temporal variation of surface wind and temperature from 0600 UTC 1 August to 0600 UTC 2 August. At MS3478, northeasterly wind dominated between 1400 UTC and 1800 UTC and a peak existed at 1500. North or northeasterly wind also dominated between 1600 UTC and 2200 UTC at the radar site and MS3608. Peaks existed at the radar site and MS3608 at 1700 UTC and 1800 UTC (Figs. 22b and 22c). These variations and time lags of the northeasterly wind peak were consistent with the southward movement of the mesoscale cloud cluster on GMS images and radar echoes. They indicated that the north and northeasterly wind accompanied the movement of the stratiform echo movement. At the radar site, there was a second peak of the northeasterly wind at 1900 UTC, and the northeasterly wind lasted until 2030 UTC. The period of northeasterly wind agreed with that of the convergence in the lower layer obtained by the VAD analyses (Fig. 20b). The rainfall at the only radar site lasted for seven hours. At MS3478 and MS3608, no second peak existed and rainfall was not strong. These results of the surface wind and VAD analyses suggests that the mesoscale con-
The radar was operated continuously for four months, and the TRMM satellite, which carries the world’s first satellite-borne precipitation radar (PR), observed the rainfall over the Tibetan area. We studied the characteristics of the stratiform rainfall over the plateau using the radar, TRMM PR data, objective analysis data, sounding data, rain gauges, a thermometers, wind vanes and anemometers.

Using the area-averaged rain rate, storm height,
and rain type parameter of TRMM PR, we detected a diurnal variation of the rain within the mesoscale observation area on the Plateau during the IOP, convective precipitation in the afternoon that has a high storm height value, and stratiform precipitation in the evening and night that has a low storm height and broad rain area. The variation was the basic characteristic of the rainfall in the GAME-Tibet mesoscale analysis area.

The major findings from the analyses of the two case studies are summarized below.

In Case 1 (7 and 8 July 1998), stratiform precipitation was observed in the evening and night. The variations in GMS/IR cloud images on 7 and 8 July 1998 were similar. In the daytime, small cloud clusters developed linearly from east-northeast to west-southwest near the radar site. The clusters then merged and broadened over the radar site in the evening and night, and disappeared by morning. However, the other characteristics of the two days were different. On 7 July, a synoptic convergence area developed in the southern part of the Plateau at 1200 UTC. Small convective echoes and stratiform echoes coexisted in the radar coverage at the beginning of the rainfall. Stratiform precipitation then lasted for 12 hours. Southwesterly wind dominated above 6 km ASL, but the wind direction below 6 km ASL was variable.

A convergence line between southwesterly wind and northerly wind was detected using the daily mean of the synoptic field revealed by the six-hourly objective analysis data on 8 July. A synoptic convergence zone passed over the radar site at 1200 UTC on 8 July. The equivalent potential temperature abruptly decreased below 8 km ASL after 1200 UTC. These results indicated a cold frontal passage over the radar site. A sudden wind direction change from westerly to northwesterly was observed below 8 km ASL from the vertical profiles at the radar site revealed by the VAD method. The boundary between northwesterly and northerly wind may correspond to the cold frontal surface. However, the precipitation with the frontal passage was stratiform and had a low echo top. Rainfall on 8 July was weaker than that on 7 July. After the passage of the cold front, the precipitation on the plateau was weak for 10 days (Fig. 3).

In Case 2 (1 and 2 August 1998), there was no remarkable disturbance in the synoptic field. The variation of the divergence field from GHANAL was similar to that of Case 1 (7 July 1998). A divergence area existed around the radar site at 1800 UTC on 1 August, but much rainfall (exceeding 4 mm/h) was observed. There were no convective echoes, and a 90 km-diameter stratiform echo stayed over the radar site for nine hours. This variation corresponded well to the variation of clouds in the GMS/IR images.

Weak easterly or no wind dominated above 6.5 km ASL in Case 2. Below 6.5 km ASL, the wind direction varied from northerly to northeasterly, then to easterly. The wind variation corresponded to the wind change at the surface. Convective in the lower layer and divergence in the upper layer dominated during the rain. From 1800 UTC to 2100 UTC when northeasterly wind dominated, convergence in the lower layer strengthened and much stratiform precipitation was observed. The northerly and northeasterly wind moved southward with the movement of the radar echo cluster.

The characteristics of the stratiform precipitation in the case studies judged from our analyses are summarized as Table 3. We can divide Case 1 into two periods, 7 July and 8 July. The common characteristics of the stratiform rainfall in the case studies are as follows.

- Moist air with a relative humidity exceeding 80% existed below 9 km ASL.
- The wind above 6 km ASL did not change so much during stratiform precipitation.
- The stratiform precipitation developed when the wind below 6 km ASL varied and convergence in the radar coverage strengthened.

Stratiform rainfall in the evening and night contributed to the rainfall in the mesoscale observation area on the Tibetan Plateau in the case studies. The rainfall variation of Case 1 was consistent with the diurnal variation revealed by TRMM PR. The passage of the cold front did not contribute so much to the development of the precipitation on the plateau. Mesoscale convergence of moist air in the lower layer may contribute more effectively to development of stratiform rainfall than the passage of the cold front. In Case 2, no convective rain existed in the evening and the rain fell in the mid-night. The stratiform echo, that had a 90 km diameter and moved from the north, was maintained by mesoscale convergence caused by the intrusion of the northerly and northeasterly wind with the moist air. In both cases, mesoscale convergence of moist air in the lower layer was important for evolution of the stratiform rainfall. However, the wind direction in the lower layer was not constant, and we have not detected the source of the mesoscale
Table 3. Classifications for features and kinds of value of precipitation systems.

<table>
<thead>
<tr>
<th>Rain Type</th>
<th>Rainfall(mm./hours)</th>
<th>Maximum Rainfall Time (UTC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1 (7 July 1998)</td>
<td>Convective → Stratiform</td>
<td>20.3/15</td>
</tr>
<tr>
<td>Case 1 (8 July 1998)</td>
<td>Stratiform</td>
<td>9.2/9</td>
</tr>
<tr>
<td>Case 2 (1 August 1998)</td>
<td>Stratiform</td>
<td>20.0/7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dominant Wind Direction</th>
<th>Divergence Profile (Upper/Lower)</th>
<th>Relative Humidity Change at 6km ASL (12Z−00Z, %)</th>
<th>Frontal Passage</th>
</tr>
</thead>
<tbody>
<tr>
<td>N→SW→SE→N</td>
<td>Divergence/Convergence</td>
<td>100 → 97</td>
<td>No</td>
</tr>
<tr>
<td>W→NW</td>
<td>Divergence/Convergence</td>
<td>86 → 38</td>
<td>Yes</td>
</tr>
<tr>
<td>N→NE</td>
<td>Divergence/Convergence</td>
<td>94 → 59</td>
<td>No</td>
</tr>
</tbody>
</table>

convergence.

The pattern of the divergence profiles, that is the convergence in the lower layer and divergence in the upper layer, lasted for a long time. In the convective rainfall cases, the mesoscale convergence may be stronger and shorter than in the stratiform rainfall cases. Because the VAD method cannot be used for convective precipitation, we cannot confirm this expectation. A wind profiler network will probably be useful for analyzing the mesoscale convergence field.

In this paper, we chose only two case studies. However, we collected much data on precipitation in the Tibetan Plateau. We have not yet detected common characteristics of the mesoscale stratiform rainfall. We should classify stratiform rain types on the Tibetan Plateau and draw models of precipitation on the Tibetan Plateau using the voluminous GAME-Tibet data and numerical analyses.

Acknowledgments

The authors would like to express their gratitude to the Chinese, Korean and Japanese members of the GAME-Tibet observation group for their helpful cooperation in the observations on the Tibetan Plateau. Thanks are also due to Ms. Misako Kuchi, NASA EORC, for her advice on how to handle the analysis tools and huge volume of data. They would also like to express their thanks to the Remote Sensing Technology Center of Japan (RESTEC) for processing the TRMM PR data and to Dr. Nobuhiko Endo, Frontier Research System for Global Change, for providing the data set of GPS rawinsonde. They are grateful to Dr. Tokio Kikuchi, Kochi University, for providing valuable GMS data. Thanks are likewise extended to Dr. Kiyotoshi Takahashi, Meteorological Research Institute, for providing valuable GAME data. The data used in the paper was obtained through the GAME-Tibet project supported by the Ministry of Education, Science, Sports and Culture of Japan; the Science and Technology Agency of Japan; the Chinese Academy of Science; the Frontier Research System for Global Change; the National Space Development Agency of Japan; and the Asian Pacific Network.

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