CASE STUDY ON THE FORMATION OF SNOWFALL IN A BASIN COVERED BY THE STRATIFORMED PRECIPITATION SYSTEM WITH AN EXTRATROPIC CYCLONE IN WINTER

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1. INTRODUCTION

In winter, a stratiformed precipitation system often extends widely with an extratropical cyclone moving on the Pacific coast of Japanese archipelago (Takano 2002). When the stratiformed precipitating system covers on the central Japanese archipelago including basins and plans, snowfall or rainfall occurs. Discriminants of snowfall or rainfall, however, don't depend on such cold and warm regions in a simplistic form.

As a brief cloud-physical structure, a stratiformed precipitating system generally includes snowflakes and other ice particles at the upper layer and raindrops at the lower layer across a melting layer at the middle layer (Houze 1981). Kain et al. (2000) indicated that melting snow made the level of 0 degree Celsius (°C) fall to surface. Then, rainfall at surface changed to snowfall. To enable the discriminant of snowfall or rainfall, however, the formation of snowfall at surface in a stratiformed precipitating system has not been understood enough.

Kofu Basin located in the Central Japanese archipelago is at about 300 m above the sea level (ASL) and is surrounded by mountains with the elevation of 1 to 2 km (**Fig. 1**). Shizuoka area is located in the coastal region on the south of Kofu Basin. When an extratropical cyclone moves on the Pacific coast of Japanese archipelago in winter, the stratiformed precipitating system covers on Kofu Basin and Shizuoka area. In that event, snowfall or rainfall often occurs at Kofu Basin, while rainfall usually occurs at Shizuoka area.

At Kofu Basin and Shizuoka area, X-band multi-parameter radars (hereafter, X-MPRs) are operated on a steady basis by University of Yamanashi and Ministry of Land, Infrastructure, Transport and Tourism (MLIT); they observed some cases of the stratiformed precipitating system associated with an extratropical cyclone moving on the Pacific coast of Japanese archipelago which brought snowfall at Kofu Basin and rainfall at Shizuoka area in winter. In the present study, we analyze the structure of the stratiformed precipitating system which brought snowfall at Kofu Basin and rainfall at Shizuoka area using the case study of the X-MPRs observation mainly. From the result, we discuss the formation of snowfall in a basin covered by the stratiformed precipitation system associated with the extratropical cyclones.

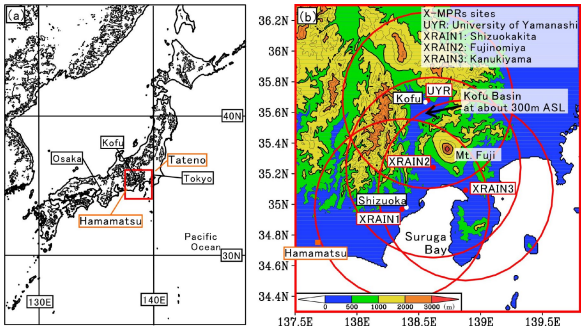

Fig.1 (a) Map of Japanese archipelago. (b) Terrains in the red rectangle in (a) with the observation ranges and sites of X-MPRs (red with dots), the JMA observatories at Kofu and Shizuoka (white dots) and Sounding observation at Hamamatsu (orange square).

2. DATA

For the analyses, we use the observation data of X-MPRs operated by University of Yamanashi (hereafter, UYR) and Ministry of Land, Infrastructure, Transport and Tourism (hereafter, XRAINs), the composited rainfall intensity data at 2 km ASL observed by C-band radar of Japan Meteorological Agency (hereafter, the JMA), surface meteorological data at observatories and routine observation points of the JMA, weather charts published by the JMA and sounding observation data (**Fig. 1b**). Almost JMA observatories locate in plains and basins in Japanese archipelago below the level of 1 km ASL. Local Standard Time (LST = UTC + nine hours) is used.

3. APPEARANCE OF PRECIPITATION TYPE IN KOFU AND SHIZUOKA

The cases of the extratropical cyclones moving on the Pacific coast of Japanese archipelago were 13 cases out of 1 December on 2012 to 28 February on 2013. Six cases of them were snowfall and sleet events at Kofu and rainfall at Shizuoka (**Fig. 2**). As one of the examples, we selected the case on 14 January 2013 because snowfall was strong and snow depth was the largest in the cases.

	2012						2013						
	4 Dec.	6 Dec.	8 Dec.	22 Dec.	28 Dec	30 Dec.	14 Jan.	22 Jan.	2 Feb.	4 Feb.	6 Feb.	13 Feb.	18 Feb.
Kofu	●	●	✳	✳ 1cm	✳ 5cm	●	✳ 10cm	●	●	●	●	✳ 2cm	✳ 0cm
Shizu-oka	●	●	●	●	●	●	●	●	●	●	●	●	●

✳: Show with maximum snow depth ✳: Sleet ●: Rain

Fig.2 Surface precipitation type at the JMA observatories at Kofu and Shizuoka. Value with snow mark indicates maximum snow depth.

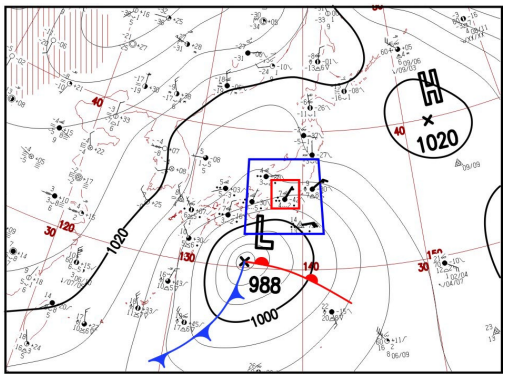

Fig.3 Weather chart at surface at 0900 LST on 14 January 2013.

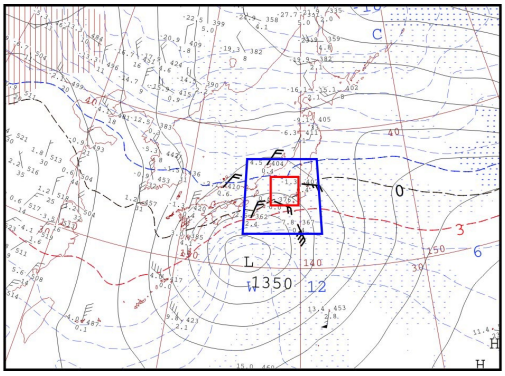

Fig.4 Weather chart at the level of 850 hPa at 0900 LST on 14 January 2013.

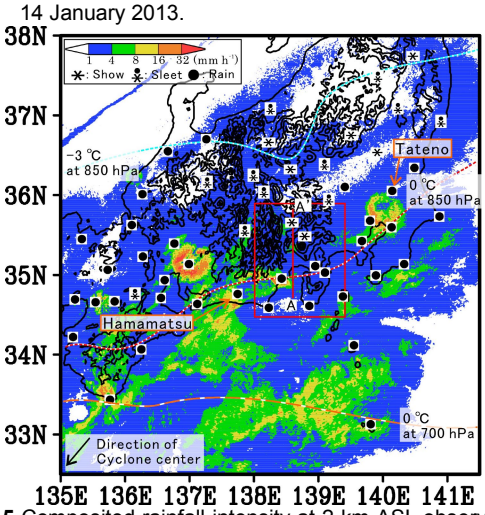

Fig.5 Composited rainfall intensity at 2 km ASL observed by C-band radar of the JMA with weather condition at each JMA observatory at 0900 on 14 January 2013. Colored and dashed lines indicate isothermal lines derived by upper weather charts. This region corresponds to the blue rectangle in **Figs. 3 and 4**.

4. OVERVIEW OF THE STRATIFORMED PRECIPITATING SYSTEM WITH THE EXTRATROPICAL CYCLONES MOVING ON THE PACIFIC COAST OF JAPANESE ARCHIPELAGO ON 14 JANUARY 2013

At surface, Kofu Basin and Shizuoka area were located in the northeastern region with northeasterly wind of the extratropic cyclone at sea off the south of Japan archipelago (**Fig. 3**). At the level of 850 hPa, westerly to south-southeasterly wind with warm and moist air blew to Kofu basin and Shizuoka area (**Fig. 4**).

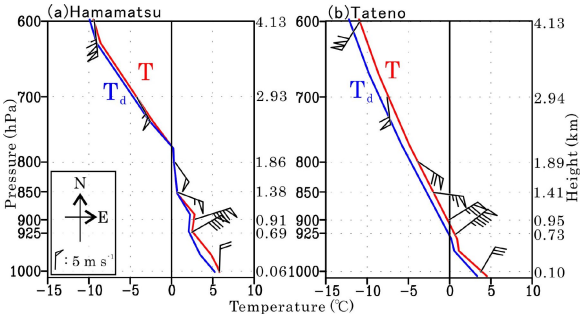

Fig.6 Sounding profiles at (a) Hamamatsu and (b) Tateno at 0900 LST on 14 January 2013.

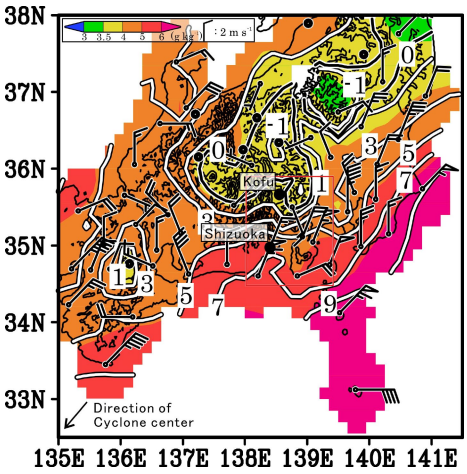

Fig.7 Surface water vapor mixing ratio (color shaded regions), surface temperature (white contours, unit ℃) and surface wind (barbs) derived by the surface observation at the JMA observatories at 0900 LST on 14 January 2013. This region corresponds to the blue rectangle in **Figs. 3 and 4**.

Stratiformed precipitating system extended from the ocean to the central region of Japanese archipelago (**Fig. 5**). The level of 0 ℃ decreased from ocean side to central region of Japan archipelago with strong rainfall intensity in the stratiformed precipitating system. Rainfall was observed at the JMA observatories at the Pacific coast and on the Plain. On the other hand, snowfall and sleet were observed at the JMA observatories in basins and valleys.

From the sounding observation at Hamamatsu under the stratiformed precipitating system, the isothermal layer with temperature of 0 to 0.5 ℃ appeared from 1.4 km ASL to 2.0 km ASL (**Fig. 6a**) The isothermal layer with temperature of about 0.5 ℃ also appeared at 0.5 to 0.73 km ASL at Tateno (**Fig. 6b**). Findeisen (1940) pointed out the existence of the isothermal layer with temperature of 0 ℃ in nimbostratus. Winds at Hamamatsu and Tateno rotated clockwise from the lowest layer to about 2 km ASL. Warm advection with moist air developed below 2 km ASL on the northeastern region of the extratropic cyclone. Then, the isothermal layer of about 0 ℃ formed below 2 km ASL and the altitude decreased toward northern side

At surface, strong northerly to northeasterly surface wind with high water vapor mixing ratio and

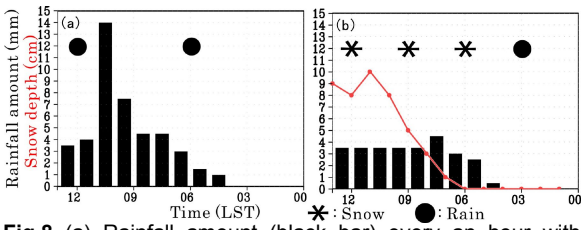

Fig.8 (a) Rainfall amount (black bar) every an hour with precipitation type at Shizuoka and (b) rainfall amount (black bar) and snow depth (red line with dots) every an hour with weather condition at Kofu from 0000 LST to 1300 LST on 14 January 2013.

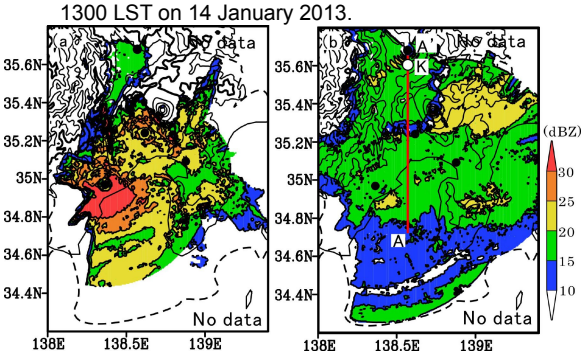

Fig.9 The horizontal sections of composited radar reflectivity observed by X-MPRs at (a) 1 km ASL and (b) 2.5 km ASL at 0900 LST on 14 January 2013. This region corresponds to the red rectangles in **Figs. 5 and 7**.

temperature blew at the Pacific coast and on the plain (**Fig. 7**), which means rainfall with warm advection. In basins and valleys with snowfall and sleet, temperature maintained -1 to 0 $^{\circ}$C and water vapor mixing ratio maintained 3.5 to 4 g kg $^{-1}$ with height. Furthermore, no or very weak wind blew. Although the same stratiformed precipitating system was covered, snowfall and sleet in basins and valleys at the central region of Japanese archipelago were occurred under calm condition.

5. STRUCTURE OF THE STRATIFORMED PRECIPITATING SYSTEM COVERED FROM SURUGA BAY TO KOFU BASIN

When the stratiformed precipitating system covered from Suruga Bay and Kofu Basin, rainfall occurred at Shizuoka on the coastal region of Suruga Bay (**Fig. 8**a). At Kofu city in Kofu Basin, rainfall changed to snowfall from 0300 LST to 0600 LST (**Fig. 8b**). After 0600 LST, snowfall continued and snow depth increased although snow depth decreased from 1100 LST to 1200 LST. X-MPRs observed the the stratiformed precipitating system covered from Suruga Bay with rainfall and strong wind to Kofu Basin with snowfall under calm condition.

Figure 9 shows the horizontal sections of composited radar reflectivity observed by X-MPRs (hereafter, Z_H). At 1 km ASL, strong Z_H extended on Suruga Bay and the coastal region, while weak Z_H existed in Kofu Basin (**Fig. 9a**). Weak Z_H covered from Suruga Bay to Kofu Basin at 2.5 km ASL (**Fig 9b**).

Figure 10 shows temporal variation of the vertical sections of Z_H. At 0300 LST, weak Z_H was falling to

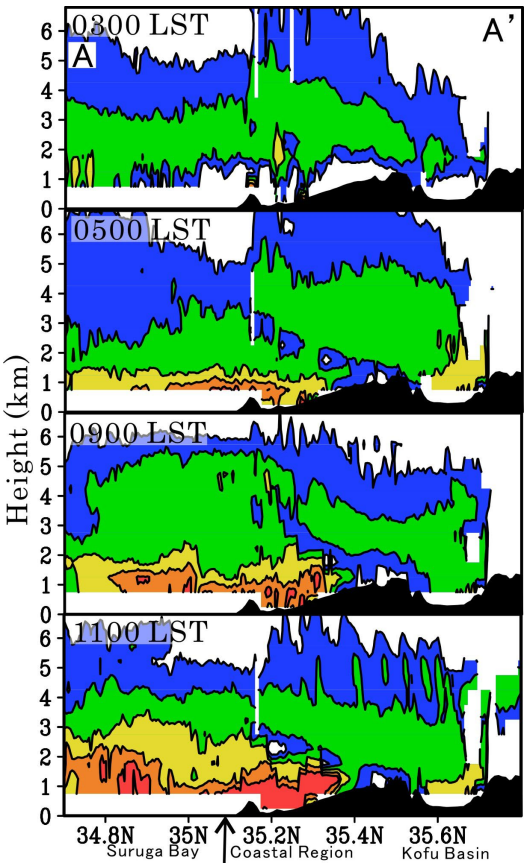

Fig.10 Temporal variations of the vertical sections of composited radar reflectivity observed by X-MPRs along the line A – A' in **Fig. 5 and Fig. 7b**.

Suruga Bay, the coastal region and Kofu Basin from the upper layer. On Suruga Bay and the coastal region stratiformed strong Z_H appeared below 1.5 km ASL from 0500 LST, which is a brightband. Afterward, the brightband developed below 2 km ASL. It is suggested that melting with warm advection at the lower layer on Suruga Bay and the coastal region caused much rainfall (**Fig. 8a**).

On the other hand, weak Z_H continued to fall to Kofu Basin from the upper layer although falling Z_H in Kofu Basin developed slightly at 0500 LST and 1100 LST. We consider that, although rainfall was observed occasionally, snow above the brightband fell to Kofu Basin without melting, which contributed to much snowfall (**Fig. 8b**)

6. METEOROLOGICAL CONDITION IN KOFU BASIN WITH CHENGE FROM RAINFALL TO SNOWFALL

We describe the meteorological condition in Kofu Basin when rainfall changed to snowfall. **Figure 11a** shows time-height section of correlation coefficient (ρ_{HV}) and wind derived VAD method at point K in **Fig. 9b**. These data derived by the UYR observation. Low ρ_{HV} region appeared at 1 km ASL at 0300 LST. The low ρ_{HV} region arrived at Kofu Bain at 0400 LST. From 0500 LST, the thickness of low ρ_{HV} region

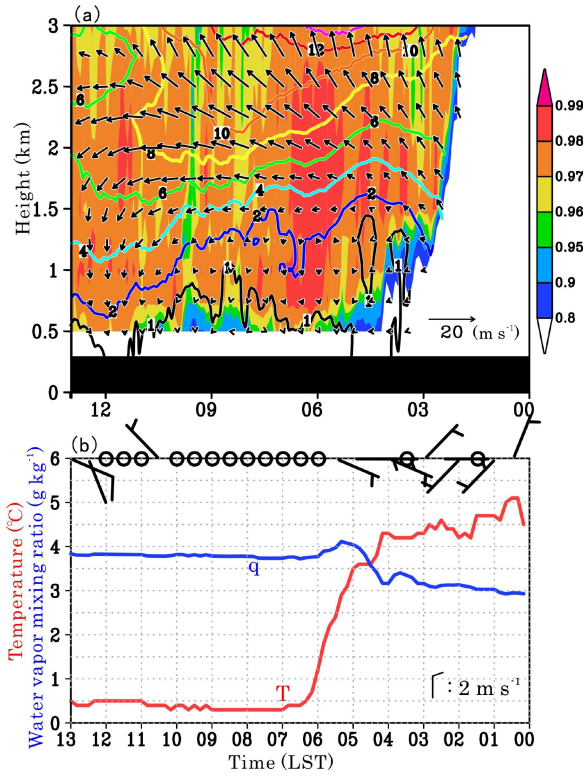

Fig.11 (a) Time-height section of correlation coefficient (color shaded region) and wind derived VAD method (vectors and color contours (wind speed)) at point K in Fig. 7b. They were derived by UYR observation. (b) Surface temperature (red line) and water vapor mixing ratio (blue line) every 10 minutes and surface wind (barbs) every 30 minutes at Kofu.

decreased; high ρ_{HV} region above the low ρ_{HV} region fell to Kofu Basin. The high ρ_{HV} region arrived at Kofu Basin at 0600 LST. Afterward, ρ_{HV} value repeatedly increased and decreased below 0.75 km ASL in Kofu Basin. For the period, wind below 1.5 km ASL was weak.

Figure 11b shows temporal variations of temperature, water vapor mixing ratio and wind at Kofu observatory at 273 m ASL. From 0400 LST to 0500 LST, temperature decreased about 1 °C and water vapor mixing ratio increased about 1 g kg^{-1}. From 0500 LST to 0620 LST, temperature decreased about 3 °C abruptly and linearly. Then, water vapor mixing ratio decreased slightly. For the period, wind was very weak. Afterward, temperature and water vapor mixing ratio maintained about 0.5 °C and 3.8 g kg^{-1} with calm, respectively.

According to precipitation type, rainfall amount and snow depth (**Fig. 8b**), we consider that the decrease of temperature from 0400 LST and 0500 LST was caused by evaporative cooling associated with rainfall. From 0500 LST, it is suggested that cold air with snow and the temperature of about 0 °C fell to Kofu Basin. Stewart et al. (1984) indicated the isothermal layer with temperature of 0 °C above the brightband.

We analyzed surface temperature at routine observation points of the JMA in Kofu Basin. There are 5 observation points at the height from 226 m ASL to 867 m ASL (**Fig. 12a**). At Oizumi (867 m ASL) and

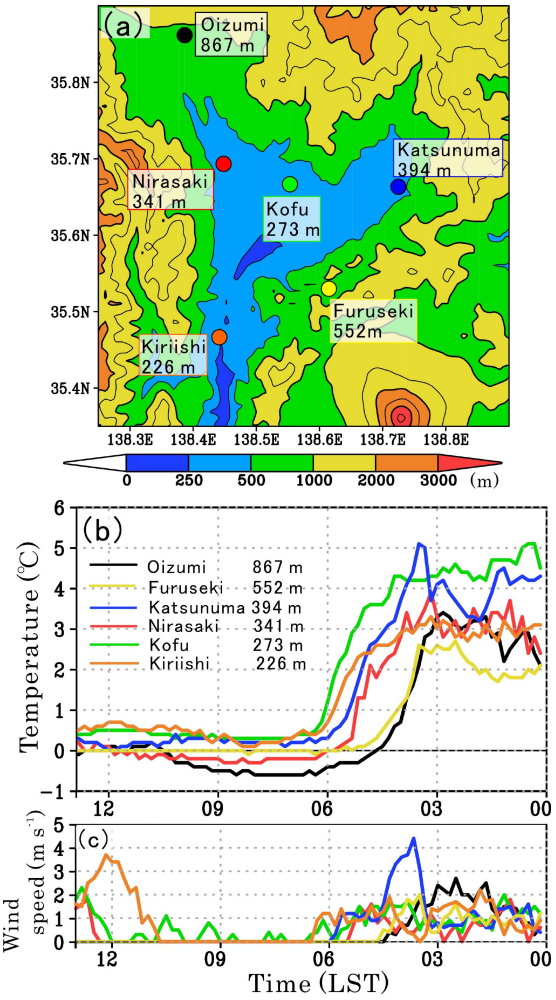

Fig.12 (a) Terrains and routine observation points of the JMA in Kofu Basin. (b) Temperature every 10 minutes and (c) wind speed every 10 minutes at the observation points from 0000 LST to 1300 LST on 14 January 2013.

Furuseki (552 m ASL), temperature decreased exponentially toward 0 to -0.5 °C from 0300 LST to 0600 LST (**Fig. 12b**). At Katsunuma (394 m ASL) and Nirasaki (341 m ASL), temperature also decreased exponentially about 3 °C from 0300 LST to 0500 LST. From 0500 LST to 0600 LST, however, temperature at Katsunuma, Nirasaki and Kiriishi (226 m ASL) decreased abruptly and linearly toward about 0 °C, which is similar to the temporal variation of temperature at Kofu (**Fig. 11b**). From 0600 LST, temperature at all points was maintained within a range of -0.5 to 0.5 °C with calm (**Figs. 12b and 12c**).

6. DISCUSSION

From the results, we consider the formation of snowfall in Kofu Basin as follows. Precipitation came from the upper layer above the melting layer in the system (**Fig. 13a**). The air in Kofu Basin was cooled by evaporation and melting associated with rainfall first. Then upper air in Kofu Basin became about 0 °C and snow existed (**Fig. 13b**). Finally, it is suggested that, falling the upper cold air, air in Kofu Basin changed from cool air with rain to cold air with snow and

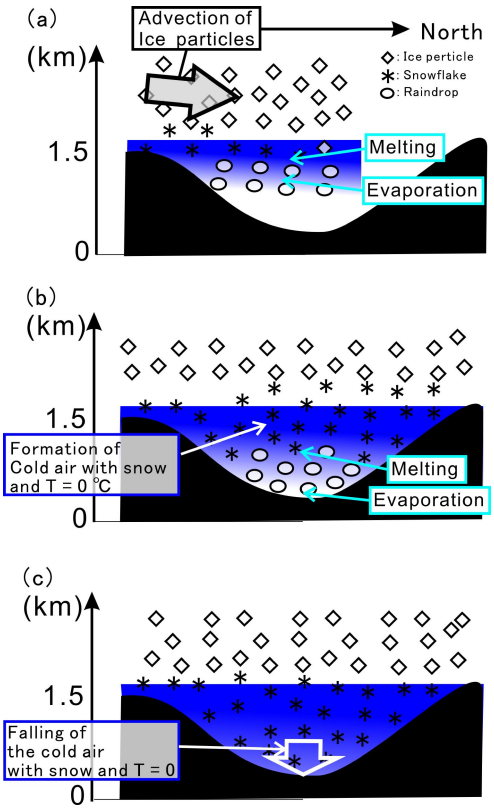

Fig.13 Conceptual image of the formation of snowfall in Kofu Basin.

temperature of 0 ℃ (**Fig. 13c**). At the result, snowfall formed in Kofu Basin.

Furthermore, no warm advection from outer side of Kofu Basin appeared because of surrounding mountains. Thus, we consider that snowfall in Kofu Basin was maintained for a long time.

7. SUMMARY

In the present study, the formation of snowfall in a basin brought by the stratiformed precipitation system associated with the extratropical cyclones moving on the Pacific coast of Japanese archipelago was analyzed as a case study.

On 14 January 2013, precipitation brought by the stratiformed precipitating system associated with the extratropic cyclone moving on the Pacific coast of Japanese archipelago. On the Pacific coastal region and plains, rainfall was brought by the system formed the melting layer with warm advection at the lower layer. On the other hand, snowfall and sleet were occurred in basins and valleys at the central region of Japanese archipelago under calm conditions.

As one of the basins with snowfall, we analyzed the formation of snowfall in Kofu Basin. Precipitation came from the upper layer above the melting layer in the system. The decrease of temperature in Kofu Basin was caused by evaporative and melting cooling associated with rainfall. Then, upper air in Kofu Basin became about 0 ℃ and snow existed. Afterward, it is suggested that, the upper cold air fell to Kofu Basin, air in Kofu Basin became cold air with snow and temperature of 0 ℃. Thus, snowfall formed and maintained in Kofu Basin without warm advection.

It is mentioned that this result is one of the formation process of snowfall in basins associated with a stratiformed precipitation system with an extratropical cyclone moving on the Pacific coast of Japanese archipelago.

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