A Medium-Scale Cloud Cluster in a Baiu Front

Part I: Evolution Process and Fine Structure

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Abstract

Evolution process and fine structure of a medium-scale (~ 1000 km) cloud cluster developed over the western portion of the Baiu front (Continental China region) and propagated to the eastern portion (the Japan Islands and the Pacific) are investigated. In this paper (Part I), special attention is put on variations in cloud/rainfall features, associated disturbances and environmental situations throughout evolution process of the cloud cluster.

This cloud cluster was generated at the eastern foot of the Tibetan Plateau 12 July 1979, and propagated to the east toward the Japan Islands, along $\sim 30^\circ\text{N}$ latitude circle with a phase speed of ~ 1000 km/day. Two days after its generation, the cloud cluster caused heavy rainfalls (~ 100 mm in one hour) over the southwest Japan. After this, the cluster developed into a depression as it propagated over the Pacific along the subtropical baroclinic zone (the Baiu frontal zone). The following features are found:

- 1). This medium-scale cloud cluster had a long life time (a few days). Its shape seen in GMS images changed evidently during the analysis period (12GMT, 12 July $\sim$ 12GMT, 15 July). The evolution process is subdivided into four stages, i.e., formation, developing, transitional and cyclone-formation stages.

- 2). Over the Continent (formation and developing stages), the cloud cluster has an isolated oval-shape and developed associating with a weak positive vorticity core which was embedded in the southern branch of the mid-tropospheric jet stream (southern frontal zone). This positive vorticity core is thought to be formed by lee-cyclogenesis due to the Tibetan Plateau. Over Japan and the Pacific (cyclone-formation stage) the cloud cluster was elongated in shape and developed into a depression in the baroclinic zone (Baiu front), coupled with a short wave trough in the upper troposphere, which was propagated southeastward from the northern frontal zone over the Continent.

- 3). Cloud/rainfall features of the cloud cluster over the Continent were quite different from those observed over the Japan Islands. That is, the cloud cluster developed in the unstable tropical air over the Continent consisted of only convective clouds. In contrast to that, the cluster in the subtropical baroclinic zone consists of both convective and stratiform clouds, or convective and uniform echoes as recognized in radar.

- 4). Rainfall in the cloud cluster reached a maximum intensity at the end of the developing stage. After this, the cluster shrank in extension, as the positive vorticity core in the middle layer became less distinct. In the cyclone-formation stage, rainfalls reached another maximum, which was followed by the transformation of the cluster into a large cloud system of a frontal depression.

- 5). The cluster was composed of a few mesoscale (~ 100 km) cells. The minimum of T_{BB} in the mesoscale cells was $\sim -70^\circ\text{C}$ (cloud top height of ~ 16 km).

- 6). The cloud cluster showed periodic variation with a period of several hours throughout the four stages. This variation is attributed to alternate developments of mesoscale cells within the cluster.

- 7). A detailed comparison of radar observations with GMS T_{BB} maps was made for the cyclone-formation stage. In macroscopic, areas of organized convective echoes were dis-

tributed in the southern part of the cluster and those of uniform echoes were in the northern part, each of which coincided with the areas of convective and stratiform clouds in the cluster respectively.

8). The cloud cluster showed a periodic variation of about one day; development in the early morning (18GMT–00GMT) and shrinkage in the early afternoon (~06GMT). This variation was related with large-scale changes in thermal and wind fields.

9). Mesoscale fine structures in the cloud cluster is commonly observed for the Continent and the Japan Islands, despite that the associated disturbances and cloud/rainfall features were different between over the two regions.

10). It is concluded that the long life time of the cloud cluster is due to the change of associated disturbances.

1. Introduction

Meteorological satellite observations have revealed organized convective cloud systems over various parts of the world. Tropical cloud clusters and squall lines have been studied by a number of authors (e.g., Martin and Sikdar, 1975, 1979, for BOMEX area; Ruprecht and Gray, 1976 a and b, for West pacific and West Indian sea; Ogura *et al.*, 1979, for GATE area). Recently a somewhat different type of cloud clusters[†] over the mid-latitudes of the North America has been studied (e.g., Hoxit *et al.*, 1978; Maddox, 1980). Bosart and Sanders (1981) have reported a case of long-lived cloud cluster for small size (about 1000 km in diameter). However, the mechanism of their long life time was not examined; fine structures of the clusters were not fully described in those studies.

Convective cloud systems (clusters) develop also over the East Asia in summer season. Especially medium-scale (wavelength of about 1000 km) cloud clusters accompanying medium-scale disturbances frequently develop in a Baiu front (Matsumoto *et al.*, 1970; Ninomiya and Akiyama, 1971, 1972, 1973; Yoshizumi, 1977; Akiyama, 1978, 1979). Sometimes they cause heavy rainfalls over the Japan Islands. Meteorologists in Japan have studied these disturbances on thermodynamic structure, cloud and radar echo features and associated rainfalls (op. cit.). Those studies, however, were limited to cloud clusters situated over the

Japan Islands, because of data restriction.

Since GMS was in operation, it has become possible to investigate short-period variations of cloud features over the East Asia. Some authors (Narikawa, 1980; Ninomiya *et al.*, 1981) have noticed that medium-scale cloud clusters over Japan are propagated from the Continental China region. Narikawa (1980) reported that a cloud cluster was generated at the southeastern foot of the Tibetan Plateau at 00GMT, 12 July 1979 and propagated to the east along ~30N latitude circle, and that it caused heavy rainfalls over the Japan Islands ~18GMT, 14 July, *i.e.*, two days after its generation. Paying attention to its long life time and change in shape, Ninomiya *et al.* (1981) made a preliminary study on properties of convections, associated circulation systems and evolution process of the same cloud cluster. Since those papers are very brief observational documentations, a further study of the cloud cluster is needed.

In Part I of the present paper, the author intends to elucidate evolution process, nature of the associated disturbance, rainfalls and mesoscale fine structure in the cloud cluster during 4-day period from its generation to transformation into a large cloud system of a frontal depression, by utilizing mainly GMS IR pixel data, FGGE LEVEL-II b data set and radar data. The author's attention will be focused on differences in cloud/rainfall features and environmental situations of the cloud cluster between over the Continent and over the Japan Islands.

2. Data

Data utilized in this paper are as follows:

[†] Maddox (1980) defined them as MCCs from cloud features on GMS images and examined statistically the occurrence frequency and life time of them over U.S.A.

Satellite data

3-hourly GMS HIMAWARI infrared pixel data converted into T_{BB} (equivalent black body temperature) are utilized. In addition, observations made at 30 min intervals are utilized for the periods from 1003GMT to 1133GMT and from 2203GMT to 2333GMT. Horizontal resolution of one picture element (pixel) is ~ 6 km at $\sim 140^\circ\text{E}$ longitude of $\sim 30^\circ\text{N}$ latitude and ~ 8 km at $\sim 100^\circ\text{E}$ of $\sim 30^\circ\text{N}$.

Radar data

Three radar (FUKUOKA, $33^\circ 26'\text{N}$ $130^\circ 22'\text{E}$, TANEGASHIMA, $30^\circ 38'\text{N}$, $130^\circ 59'\text{E}$, and MUROTO, $33^\circ 15'\text{N}$, $134^\circ 11'\text{E}$) PPI pictures are used to make composite echo maps. Observation range of one radar is 300 km as indicated in Fig. 1.

SFC data

6-hourly weather reports and rainfall amounts are utilized from FGGE LEVEL-II b date set. In addition, on the Japan Islands, hourly SFC data of AMeDAS[†] are utilized. SFC stations are shown in Fig. 1, where open circles and blacked ones indicate land stations and ship stations respectively.

Grid point upper data

Grid point values at the mandatory pres-

Fig. 1 Surface stations, radar ranges and geographical features around the path of the cloud cluster. The rivers on the Continent are Chang Jiang (south side) and Huang He (north side). Only a part of AMeDAS rain gauge stations are presented in the figure. Lower figure presents 12-hourly locations of the cloud cluster on T_{BB} maps.

[†] AMeDAS (Automated Meteorological Data Acquisition System) is a dense surface observation net with spacing of ~ 20 km for rain gauges, which has been in operation by JMA since 1974.

sure levels obtained by operational Northern Hemispheric Objective Analysis system of JMA are utilized. Grid distance is ~ 380 km at 60°N latitude on polar stereographic projection map.

3. Large-scale situation

3.1 Overview on evolution of the cloud cluster

GMS infrared cloud images, 850 mb and 500 mb maps are presented in Fig. 2 for the analysis period from 12GMT, 12 July to 12GMT, 15 July 1979. The medium-scale cloud cluster (in white circle on GMS images) can be traced back to the eastern foot[†] of the Tibetan Plateau, that is, the cloud cluster was generated at the eastern foot at ~ 12 GMT 12

Fig. 2 12-hourly GMS IR images, 500 mb and 850 mb maps during the analysis period (12GMT, 12 July to 12GMT, 15 July, 1979). The cloud cluster is encircled by white line in images. Black triangles in maps show the location of the cloud cluster.

[†] Narikawa (1980) reported that this cloud cluster was generated around Assam at ~ 00 GMT 12 July.

and propagated eastward along $\sim 30^\circ\text{N}$ latitude circle. The cloud cluster had an isolated oval-shape over the Continent. As approaching the Japan Islands, the cloud cluster changed its shape into an elongated cloud system with a trail. It is seen on IR cloud images of Fig. 2 that after 12GMT 14 July, as if the cloud cluster became a part of a large cloud zone extending along $\sim 40^\circ\text{N}$ latitude circle. However, clouds spreading to the north of the cloud cluster showed high T_{BB} ($> -20^\circ\text{C}$); the low T_{BB} ($< -40^\circ\text{C}$) area of the cloud cluster was distinctly separated from the large cloud zone. From this fact, we know that the cloud cluster still sustained its identity after 12GMT 14 July.

In the $40\text{--}50^\circ\text{N}$ latitude zone, synoptic-scale lows are situated over the Continent ($\sim 110^\circ\text{E}$) and over the Okhotsk Sea ($\sim 150^\circ\text{E}$). At the east coast ($\sim 130^\circ\text{E}$) of the Continent a ridge

between the two lows extends north to south. In the $30\text{--}40^\circ\text{N}$ latitude zone, flow at the 500 mb level is rather zonal and the horizontal gradient of the isobaric height is considerably weak. In the $20\text{--}30^\circ\text{N}$ latitude zone, the subtropical high belt extends from the Pacific to the southeast of the Continent. These basic features of the large-scale circulation systems remained unchanged throughout the analysis period.

There were weak short wave troughs with a wavelength of about 2000 km moving eastward in the $30\text{--}40^\circ\text{N}$ latitude zone (see wavy contours on the 500 mb maps). In the earlier period when the trough and the cloud cluster were situated over the Continent, the trough was very weak and the relation between the

Fig. 3 The zones of the maximum mean horizontal temperature gradient $\bar{\nabla}T$ and of the maximum mean wind speed $\bar{v}$ averaged in 12GMT, 12 July $\sim$ 12GMT, 15 July. Black triangle indicates 12-hourly location of the cloud cluster.

Fig. 4 Mean mixing ratio $\bar{q}$ and mean difference between temperature T and dew point temperature T_d at 850 mb averaged in the same period as Fig. 3. Shaded areas are dry regions of $(T - T_d) > 6^\circ\text{C}$ (upper figure). Lower figure shows mean stability $(\theta_{850} - \theta_{850}^*) / \Delta p$ averaged in the same period as Fig. 3. Stipples present unstable regions.

cloud cluster and upper-level short wave troughs was not always evident. On the other hand, the cloud cluster was evidently related to a short wave trough as can be seen from the 850 mb maps of Fig. 2, in the latter period when the cloud cluster was situated over the Japan Islands and the Pacific.

The author subdivides evolution process of the cloud cluster into 4 stages, considering the aforementioned changes in features of the cloud cluster and synoptic-scale environments as following

- I. Formation stage (F stage)
12GMT, 12—15GMT, 12
- II. Developing stage (D stage)

15GMT, 12—00GMT, 14

III. Transitional stage (T stage)

00GMT, 14—12GMT, 14

IV. Cyclone-Formation stage (CF stage)

12GMT, 14—06GMT, 15

Detailed descriptions for the 4 stages will be given in section 6.

3.2 Environmental situation around the cloud cluster

At first, mean fields during the analysis period are examined to study features of environment in which the cloud cluster developed. Mean fields represent large-scale situation for the period, because the large-scale

Fig. 5 12-hourly height deviation Δz_{500} and positive vorticity ζ_{500} at 500 mb during the period from 12GMT, 12 July to 00GMT, 15 July 1979. Hatches present area of negative deviation under -10 gpm. Thin broken line indicates isoline of vorticity. Cross and black circle present the centers of the minimum height deviation and the maximum positive vorticity, respectively. The zones of the maximum wind speed at 500 mb and at 700 mb are indicated by thick line and arrows respectively. Black triangle represents the location of the cloud cluster.

situation was nearly stationary throughout the period. In Fig. 3 zones of the maximum horizontal temperature gradient ∇T and of the maximum wind speed $\bar{v}$ are presented. Upper figure of Fig. 4 shows fields of mixing ratio $\bar{q}$ and difference between temperature and dew-point temperature $(T - T_d)$ at 850 mb. Lower figure shows stability $(\theta_{e850} - \theta_{e500}^*)/\Delta p$, where θ_{e850} and θ_{e500}^* are equivalent potential temperature at 850 mb and saturated equivalent potential temperature at 500 mb respectively.

There are two strong wind zones (frontal zones) over the Continent. The northern zone (It is called as *N-frontal zone* hereafter.) lies along the zone of the maximum ∇T throughout the troposphere. On the contrary, the southern one (*S-frontal zone*) is limited below the 500 mb level and it is not associated with the zone of strong ∇T . In the 850–700 mb layer, mean

wind speed $\bar{v}$ of the *S-frontal zone* is 13–15 m/sec, while that of the *N-frontal zone* is ~ 10 m/sec at most. In other words, the *S-front* is characterized by low-level strong wind, while the *N-front* is by upper-level strong wind. The confluence of the *N* and *S* strong wind zones resulted in the formation of a single strong wind zone or the single subtropical baroclinic zone over the Japan Islands and over the Pacific, where the zones of the maximum ∇T and $\bar{v}$ shift to north with height. This is a feature of a typical baroclinic zone (frontal zone).

From the Continent to the Pacific the strong wind zone at 300 mb runs along the north side of the zone of strong ∇q at 850 mb (Fig. 4), to south of which the unstable tropical air spreads over a large area. The cloud cluster in D stage propagated along the *S-frontal zone*.

Fig. 6 12-hourly height deviation Δz_{300} and the axis of the maximum wind speed at 300 mb during the same period as Fig. 5. Stipples indicate areas of negative height deviation under -20 gpm. Thin broken line is isotach of 30 m/s. Black triangle and cross show the location of the cloud cluster and the center of the minimum height deviation, respectively.

The lower tropospheric air in and south of the S-frontal zone was very moist ($\bar{q}_{850} > 14$ gr/kg, $(\bar{T} - \bar{T}_d)_{850} < 6^\circ\text{C}$ at 850 mb). The cloud cluster in CF stage propagated eastward along the baroclinic zone. The air in the lowermost layer (SFC-850 mb) to south of the subtropical baroclinic zone is also very moist ($\bar{q}_{\text{SFC}} = 20\text{--}22$ gr/kg, $(\bar{T} - \bar{T}_d)_{\text{SFC}} < 3^\circ\text{C}$ at SFC).

3.3 Disturbances associated with the medium-scale cloud cluster

To look into the short wave troughs described in subsection 3.1 in more detail, height deviation Δz was calculated by

$$\Delta z = \begin{cases} z - \bar{z}_{00} & \text{for 00GMT} \\ z - \bar{z}_{12} & \text{for 12GMT} \end{cases}$$

where z_{00} , z_{12} and bar (—) indicate the geopotential height observed at 00GMT, 12GMT and time mean for the analysis period. This procedure was made to exclude large diurnal variation in the inland area. The deviation fields of z at the 500 mb and 300 mb levels are presented together with axes of strong winds in Figs. 5 and 6 respectively. A distinct short wave trough propagated to the east along the northern jet axis (the N-frontal zone) over the Continent. The trough was, however, obscure in the lower layer (850-700 mb) over the Continent. The trough deepened over the East China Sea and the Pacific, propagating southeastward along the baroclinic zone. In CF stage the cloud cluster was deeply related to the short wave trough.

A few separated positive vorticity cores existed at the 500 mb level as illustrated in fig. 5 by broken lines. One of them is associated with the distinct short wave trough moving along the N-frontal zone. Over the

Fig. 7 Evolution stages of the cloud cluster are schematically depicted in relation to frontal zones.

Fig. 8 Sequential GMS IR/VIS cloud images of the cloud cluster at ~ 3 hour intervals during the period from 0533GMT, 13 to 0533GMT, 15 July.

Continent, however, the positive vorticity core in the *N*-frontal zone is not related to the cloud cluster which is on the *S*-frontal zone.

A core of weak positive vorticity ($\sim 8 \times 10^{-6} \text{ sec}^{-1}$) located at the eastern foot of the Tibetan Plateau at 12GMT 12 July propagated along the *S*-frontal zone over the Continent. This small core of weak positive vorticity is associated with the cloud cluster as described in Part II of the present paper. This positive vorticity core seemed to be formed by lee-cyclogenesis due to the Tibetan Plateau. This

core became obscure ($\sim 0 \times 10^{-6} \text{ sec}^{-2}$) at the east coast of the Continent, where the southern mid-level jet became weak (00GMT 14).

To summarize the aforementioned features, schematic figures of the evolution process of the cloud cluster in relation to *N*- and *S*-frontal zones are presented in Fig. 7.

4. Evolution process of the cloud cluster revealed by T_{BB} maps

It is intended in this section to describe evolution process of the cloud cluster in greater

Fig. 9 Sequential T_{BB} (equivalent black body temperature) maps of the cloud cluster at ~ 3 hour intervals during the period from 1133GMT, 12 to 0533GMT, 15 July, 1979. Outer line indicates -40°C isotherm. Isotherm interval is -10°C .

Fig. 10 Upper graph shows time variation of the minimum T_{BB} (T_{BB} of pixel) in the cloud cluster during the analysis period. Lower graphs are time variations of dimension of cloud area bounded by specified isotherms of T_{BB} .

detail, utilizing 3-hourly GMS IR data. Fig. 8 shows sequential IR/VIS cloud images of the cloud cluster from 0533GMT 13 July to 0533GMT 15 July 1979. Fig. 9 is ~ 3 hourly T_{BB} map made from IR pixel data for the analysis period (from F stage of the cloud cluster to CF stage). To express areas of active convections, cloud areas with T_{BB} lower than -40°C are depicted in Fig. 9 by drawing isolines of T_{BB} with 10°C interval. T_{BB} of -40°C and T_{BB} of -70°C correspond approximately to the cloud top heights of $\sim 12\text{km}$ (250–200 mb) and $\sim 16\text{ km}$ ($\sim 125\text{ mb}$), respectively. Fig. 10 shows time variations of the minimum T_{BB} in the cloud cluster and cloud areas having indicated T_{BB} .

The following features are found from Figs. 8, 9 and 10:

- 1). The minimum T_{BB} within the cloud cluster is $\sim -70^{\circ}\text{C}$ throughout the four stages.
- 2). As a whole, dimension of the cluster

on cloud images is almost unchanged ($\sim (500\text{ km})^2$) throughout the four stages, though the shape changed greatly.

3). Over the Continent, cloud area of the cloud cluster on GMS images (Fig. 8), approximately coincides with that on T_{BB} maps (Fig. 9). However over the Japan Islands and the Pacific, the cloud area in images is fairly large, compared with that on T_{BB} maps. The cloud cluster over the Japan Islands and the Pacific was accompanied with cloud masses with lower cloud top (T_{BB} higher than -40°C) in the north/east part of the cluster.

4). Sometimes mesoscale cellular structure is seen in the cloud cluster during the whole period.

5). Convective activity within the cluster fluctuates with a several-hour period as indicated by time variation of the coldest cloud area ($T_{BB} < -70^{\circ}\text{C}$).

6). Convective activity of the cluster also fluctuates with $\sim$ one day period as indicated by time variations of the minimum T_{BB} and convective area with $T_{BB} < -70^{\circ}\text{C}$. The area

Areas of T_{BB} lower than -40°C agreed with white brilliant cloud areas on VIS images. Emissivity of these clouds is considered to be $\sim$ unity.

of the lower T_{BB} ($< -70^{\circ}\text{C}$) expands in 18GMT–00GMT (early morning) and shrinks around 06GMT (early afternoon).

Greater detailed analyses will be given in the latter respective sections.

5. Thunderstorms and rainfalls of the cloud cluster

5.1 Thunderstorms and convective activity

Many stations reported thunderstorms in the cloud cluster throughout the four stages. Fig. 11 shows 6-hourly location of thunderstorm area determined from synoptic reports. As seen in Figs. 2 and 11, a thunderstorm area moved with the cluster. Horizontal extension of the thunderstorm area approximately coincides with that of the cloud area on T_{BB}

maps throughout the four stages. This implies that the cloud area with T_{BB} lower than -40°C is convective cloud area.

Although the minimum T_{BB} in the cluster fluctuated during the analysis period, the minimum T_{BB} was always lower than -65°C , which corresponds to the temperature at altitude of $\sim 15\text{ km}$ (see Table 1). The minimum T_{BB} sometimes dropped to $-75\sim -80^{\circ}\text{C}$. Since the temperature at the tropopause is $\sim -75^{\circ}\text{C}$, this indicates that Cb top was overshooting above the tropopause.

The peaks in time series of the minimum T_{BB} occur simultaneously with the peaks of the cloud area of $T_{BB} < -70^{\circ}\text{C}$. On the other hand, there is a time lag between peak times of the minimum T_{BB} and those of cloud area

Fig. 11 Displacement of 6-hourly thunderstorm areas (*i.e.*, the area of present weather cords $WW=13, 17, 29, 90-99$ and past weather cord $W=9$ in SYNOP) and 6-hours rainfall areas associated with the cloud cluster during the period from 12GMT, 12 to 06GMT, 15 July 1979. Black circle and numerals show the gage stations, at which the largest amount of 6-hours rainfall was recorded, and the rainfall amount. Lower figure indicates time variation of the largest amount of 6-hours rainfall (the maximum rainfall intensity in text, thick lines), and of areal averaged rainfall intensity (broken lines).

Table 1 Mean soundings in the cloud cluster averaged on 21LST, 14 July and 09LST, 15 July, 1979 for stations 47807 (33°35'N, 130°23'E) and 47827 (31°38'N, 130°36'E).

	47827		47807	
	height	temperature	height	temperature
500 mb	5850 gpm	-2.1°C	5815 gpm	-3.5°C
400	7592	-11.2	7553	-11.5
350	8602	-18.8	8561	-19.2
300	9737	-25.7	9689	-26.8
250	11032	-35.7	10974	-37.8
200	12543	-47.4	12476	-49.0
150	14386	-61.1	14301	-62.8
112*	16170	-73.2	16130	-70.1

* tropopause

of $T_{BB} < -50^{\circ}\text{C}$ or $< -40^{\circ}\text{C}$. These features indicate that the expansion of cloud area of low T_{BB} is caused by the air flowing out from the coldest center within the cloud cluster. Estimates of the expansion coefficient $1/S \cdot \Delta S / \Delta t$ of cloud area following the method proposed by Sikdar *et al.* (1970), are $\sim 10 \times 10^{-5} \text{ sec}^{-1}$ for the cloud of $T_{BB} < -40^{\circ}\text{C}$ and $\sim 30 \times 10^{-5} \text{ sec}^{-1}$ for the cloud of $T_{BB} < -70^{\circ}\text{C}$ in the period of 16GMT-18GMT, 14 July, when the cloud cluster caused heavy rainfalls of $\sim 100 \text{ mm}$ in one hour over the southwest Japan. These strong upper-level divergence implies mesoscale strong upward motion and low-level convergence within the cluster (*cf.*, Sikdar and Suomi, 1972).

5.2 Difference of rainfall features among the four stages

The cloud cluster produced rainfalls throughout the four stages. Features of rainfalls, however, varied with stages. In F stage and D stage, rainfall areas approximately coincided with thunderstorm areas and cloud areas of T_{BB} lower than -40°C ; the rains are considered to be from convective clouds. The maximum rainfall intensity was relatively weak over the Continent, except an intense rainfall ($\sim 80 \text{ mm}$ in 6 hours) which occurred at the east coast.

On the other hand, in CF stage, both convective and continuous rains were brought about by the cloud cluster. The convective rainfall was concentrated in a mesoscale area

Fig. 12 An example of one-hour rainfall maps in 15LST, 14~09LST, 15 July. Rainfall maps were made from AMeDAS rain gauge data. Radar sites are indicated by cross.

in the cluster (Fig. 12) and the maximum intensity reached 115 mm in 6 hours. The continuous rainfall (1-10 mm in one hour) area was larger than the cloud area of $T_{BB} < -40^{\circ}\text{C}$ and thunderstorm area (Fig. 11). A wide-spread cloud area of T_{BB} higher than -40°C extends to the northeast of the cloud cluster (Fig. 8). Continuous rain of 1-10 mm/hour occurred in this cloud area. Therefore averaged rainfall intensity in the whole cluster area is small, comparing with the maximum rainfall intensity (Fig. 11). In the northeastern extension, T_{BB} is $-10 \sim -20^{\circ}\text{C}$ and nearly uniform (refer to Fig. 6 of Ninomiya *et al.*, 1981). Therefore, the wide-spread cloud area of T_{BB} higher than -40°C is thought to be middle-

level stratiform cloud. Such features in cloud and rainfall distributions as described above are the very typical characteristics commonly found in medium-scale cloud clusters developed in Baiu front over the Japan Islands (Akiyama, 1979). We infer that at least some of the medium-scale disturbances in the Baiu front over the Japan Islands (e.g., Matsumoto *et al.*, 1970; Akiyama, 1978) grow from cloud clusters propagated from the Continental China.

The relationship between the maximum rainfall intensity (Fig. 11) and the coldest cloud area ($T_{BB} < -70^{\circ}\text{C}$ of Fig. 10) varies depending on the stages. The time variation of the cloud area with $T_{BB} < -70^{\circ}\text{C}$ approximately agrees with that of the maximum rainfall intensity at F and D stages, when the cloud cluster located over the Continent. At CF stage, the rainfall intensity is very large in spite of small dimension of high cloud area. The relative humidity in the lower layer over the Continent is significantly lower than that over the Japan Islands (see Part II of the present paper). Over the Continent, the evaporation from precipitating particles works to much reduce the precipitation reaching to the surface as the case of thunderstorms in USA (Newton, 1966). The large amount of rainfall over the Japan Islands would be partly due to that the evaporation from precipitating particles is very small because of high relative humidity in the lower layer.

The differences in rainfall characteristics between the earlier and later stages as described above are due to the difference in environmental situations and the change in the nature of disturbance associated with the cloud cluster. Detailed study on dynamic, thermodynamic features and moisture budget in the four stages of the cluster will be made in Part II of the present paper.

5.3 Rainfalls and evolution of the cloud cluster

At the formation stage (F stage) rainfall intensity was weak for deep convective clouds. At the end of D stage, an intense rainfall of $\sim 80\text{ mm}/6\text{ h}$ occurred. After this, the cluster shrunk with the decay of the associated mid-tropospheric cyclonic vorticity core. At T

stage, rainfall intensity decreased. It increased again at CF stage, in which the cloud cluster began to transform into an elongated cloud system of a frontal depression, coupled with a short wave trough.

It is noteworthy in the present case that the cloud cluster began to decay after the peak of heavy rainfalls at D stage. On the contrary, the cluster developed into a frontal depression after the occurrence of heavy rainfalls at CF stage. This implies that diabatic heating due to convective motions does not always accelerate the development of a medium-scale disturbance. The development of the disturbance is largely controlled by large-scale conditions such as baroclinicity of the atmosphere in the present case.

6. Evolution stages of the cloud cluster

I. Formation stage (F stage)

In 09GMT–12GMT (16LST–19LST) 12 July, several cumulonimbus clouds were formed around the eastern foot (the Szechwan Basin)[†] of the Tibetan Plateau. One of them was coupled with a mid-level positive vorticity core in the S-frontal zone, which was thought to be formed by lee-cyclogenesis due to the Plateau, and propagated northeastward, sustaining its size and shape. By 15GMT, it became identifiable as a cloud cluster. At F stage, the cloud cluster was about 1000 km apart from the N-frontal zone.

II. Developing stage (D stage)

At this stage (15GMT, 12–00GMT, 14 July), the cloud cluster propagated eastward along about 30N latitude circle and reached the east coast of the Continent, sustaining its isolated oval-shaped cloud area. At D stage, the cloud area of T_{BB} below -40°C approximately agreed with the cloud area on GMS VIS images. In other words, the cloud cluster was composed of only convective cloud (cloud top height $> \sim 12\text{ km}$). Although the coldest cloud area ($T_{BB} < -70^{\circ}\text{C}$) of the cloud cluster showed periodic variation, the cluster had a trend of development throughout this stage. It reached the maximum horizontal extension at about

[†] The Basin is situated at the upper-stream region of the Chang Jiang (a river).

00GMT, 14 July (Fig. 10), and rainfalls at D stage attained to the maximum intensity. After this, the cloud cluster shrunk rapidly in extension.

The cluster at D stage propagated along the S-frontal zone, accompanying a weak positive vorticity core (see Part II of the present paper). Thus the development of the cluster at D stage was thought to be related to the passing of a positive vorticity core in the moist unstable air. At the end of this stage, the cluster was located about 500 km south of the N-frontal zone.

III. Transitional stage (*T stage*)

At T stage (00GMT, 14–12GMT, 14 July), the cloud cluster was located over the East China Sea, shrinking in extension with weakening of the southern jet (S-frontal zone) and the positive vorticity core. At the end of this stage, however, convective activity began to be enhanced at the eastern side of the decaying cluster. That is the cluster revived at the east side and consequently retained its identity. The cloud cluster was subsequently taken over the next stage (CF stage).

Over the East China Sea, the N-frontal zone was merged with the S-frontal zone and extended to east, changing its structure into the subtropical frontal zone with baroclinicity. The upper-level short wave trough on the N-frontal zone propagated southeastward along the confluence zone, with deepening. With approaching of the trough, the cluster began to revive. At T stage, cloud features of the cluster changed from an isolated oval-shape into an elongated cloud system with a trail. In short, the environments of the cluster, the disturbances related to the cluster, cloud and rainfall features of the cluster largely changed at T stage.

IV. Cyclone-formation stage (*CF stage*)

At this stage (12GMT, 14–06GMT, 15 July) the cloud cluster propagated along 300 mb jet axis from the Japan Islands to the Pacific. The cluster was located in front of the upper-level short wave trough. At the beginning of this stage, a medium-scale disturbance (amplitude of ~ 20 gpm at 850 mb) in the lower

troposphere was associated with the cluster. At the end of this stage (~ 00 GMT, 15), the disturbance grew into a frontal depression in the baroclinic zone, coupled with the upper-level short wave trough which approached from northwest to the cluster. Cloud features of the cluster changed from a cloud system with a trail into the one elongated along the frontal zone during CF stage (see Fig. 14). Cloud areas of $T_{BB} -10 \sim -20^\circ\text{C}$ was widely spreading to northeast of the cluster. The cloud cluster produced both convective and continuous rains in this stage. The maximum rainfall intensity was recorded in this stage (see Fig. 11).

7. Fine structure in the cloud cluster and several-hour period variation

The T_{BB} maps (Fig. 9) indicate mesoscale (~ 100 km) cellular patterns (e.g., 1733GMT, 13–2333GMT, 13 July). As shown in section 8, these mesoscale patterns of low T_{BB} areas correspond to mesoscale convective echo systems observed by radar network of Japan, at least in the period of development of the mesoscale cell. Therefore mesoscale cloud cells over the Continent are considered to be mesoscale convective echo systems as well as over the Japan Islands. Fig. 13 presents sequential T_{BB} maps of ~ 30 min intervals. The right figures are T_{BB} maps for the cloud area of the cluster of T_{BB} lower than -40°C , and the left are enlarged T_{BB} maps for the cloud areas of T_{BB} lower than -70°C in the right figure.

A few coldest cloud areas of 60–70 km in diameter are aligned with intervals of 30–40 km in the cluster. They propagated eastwards with a phase speed of ~ 70 km/hour on the average, which is nearly equal to the mid-tropospheric wind speed (the cloud cluster itself moved with a phase speed of ~ 40 km/hour.). The largest rainfall intensity (Fig. 11) was recorded at the gage stations which are located on the path of these mesoscale cells. A mesoscale cell developed in a few hours, during which T_{BB} at the core of mesoscale cell dropped to the lowest value with expansion of the coldest area. Immediately after this, the coldest cloud area ($T_{BB} < -70^\circ\text{C}$)

Fig. 13 Two cases of time variation of mesoscale cells on T_{BB} maps. Right side maps are cloud area of T_{BB} lower than -40°C , and left maps are enlarged T_{BB} maps of cloud area of T_{BB} lower than -70°C in the right. Blacked area presents area of T_{BB} below -77°C .

reached the maximum extension. The mesoscale cell then decayed in the following few

hours, during which T_{BB} at the core rose with shrinkage of the coldest area. The life time of a mesoscale cell is several hours on the average. However it is different case by case and depends on dimension of the cell, as pointed out in studies on relationship between radar echo duration and dimension of echo area (Battan, 1953; Akiyama and Matsumoto, 1970).

In this case, mesoscale cells within the cluster tend to generate simultaneously in a certain period in evolution process of the cluster, and also tend to decay simultaneously. Such evolution of mesoscale cells, as a whole, resulted in the periodic variation of the cluster with the period of several hours, as seen in the time variation of the coldest cloud area ($T_{BB} < -70^{\circ}\text{C}$) of Fig. 10.

We can see finer structures within mesoscale cells (Fig. 13). There are several cores of lower T_{BB} ($< -75^{\circ}\text{C}$) in a mesoscale cell. This indicates existence of several convective cores in a mesoscale cloud cell. The fine structures of the cloud cluster described above are commonly found over the Continent and the Japan Islands, though environmental situations and associated disturbances of the cluster are largely different between the two regions.

8. Echo features in the cloud cluster revealed by PPI radar observation

It is needless to say that weather radar provides different information from GMS IR observation. The former measures radar wave reflection from precipitation in cloud, while the latter measures long-wave radiation in specified range of wavelength from cloud. Echo features in the cloud cluster located over the Japan Islands are examined, comparing with cloud area on T_{BB} maps

In Figs. 14 and 15 sequential T_{BB} maps ($T_{BB} < -40^{\circ}\text{C}$) and composite PPI radar echo maps (radar range is depicted in Fig. 1) are presented for the period of 15LST, 14 July to 09LST, 15 July (the latter half of T stage of the cluster and the former half of CF stage). In this period, shape of the cluster changed from a cloud system with a trail into an elongated system, and the associated frontal depression was in process of formation. Fig. 12 is an example of hourly rainfall maps in

Fig. 14 Sequential T_{BB} maps of the cloud cluster in 1433LST, 14 to 0833LST, 15 July 1979 (0533GMT, 14 to 2333GMT, 14 July). Outer isotherm is -40°C and isotherm interval is -10°C .

Table 2 Mean height of echo top and the air temperature at that height in echoes of weak, moderate and strong intensities, averaged in the analysis period (1500LST 14–0900LST 15 July 1979).

Echo intensity (precipitation rate)	Mean height of echo top (temperature)	Number of sample
weak (0~4 mm/hour)	6~8 km (-5°C ~ -15°C)	22
moderate (4~16 mm/hour)	8~10 km (-15°C ~ -30°C)	110
strong (>16 mm/hour)	10~12 km (-30°C ~ -45°C)	106

the period. Referring Tables 1 and 2, the following echo features are pointed out:

1). In macroscopic, echo features agree with cloud features. Along the south and west sides of the cluster, moderate/strong convective echoes develop, where T_{BB} is lower than -40°C . While in the north side of the cluster, weak uniform echo spreads widely, where T_{BB} is -10°C ~ -20°C (subsection 5.2). These echo features also coincide with rainfall features described in section 5.

2). Cloud top height is a few km higher than echo top on the average. However the cloud top height is nearly equal to the echo top height in the southwest portion of the cluster on T_{BB} maps, where moderate/strong

convective echoes are generated.

3). The trailing cloud of the cluster seen on T_{BB} maps in 18LST, 14–03LST 15 July is scarcely accompanied with echoes.

4). As the cluster becomes an elongated cloud system (06LST–09LST, 15 July), moderate/strong echoes form line-shaped structures.

5). A few mesoscale-organized convective echo systems constitute the cluster, and each system further is composed of several convective echoes.

6). In the developing period of mesoscale echo systems within the cluster, the position of them approximately coincides with that of mesoscale cloud cells seen on T_{BB} maps.

Fig. 15 Sequential 3-radar PPI composite echo maps in 1500LST, 14 to 0900LST, 15 July 1979. See radar sites and range in Fig. 1. Blacked areas and vertical-striped areas indicate strong echo and moderate echo areas respectively. Outlined area presents weak echo area. See the conversion table between echo intensity and precipitation rate in Table 2. Arrows and numerals indicate the direction and speed of the echo system's propagation.

While in the decaying period of mesoscale echo systems, the position of them does not always coincide with that of mesoscale cloud cells. Koba (1983) has also reported that mesoscale convective cloud areas (areas of low T_{BB}) do not coincide with rainfall areas in the mature and decaying stages of mesoscale convective cloud systems.

9. About one day period variation of the cloud cluster

Convective activity in the present cloud cluster showed variation of about one day period throughout the analysis period. That

is, the cluster tends to develop in the early morning (18GMT–00GMT), as indicated by increasing of cold ($T_{BB} < -70^\circ\text{C}$) cloud area and of the maximum rainfall intensity (Figs. 10 and 11). This will be related to variation in large-scale environmental circulation. As grid point data at 00GMT and 12GMT are utilized in the present paper, mean difference fields between 00GMT and 12GMT are analyzed for various quantities as $\delta A = \bar{A}_{00} - \bar{A}_{12}$, where $\bar{A}_{00}$ and $\bar{A}_{12}$ are averages of the 00GMT and 12GMT observations in the 4-day period (12–15, July 1979), respectively. Mean difference fields are presented in Figs. 16, 17 and 18.

Differences in the nature of underlying surface (sea and land), cloud cover, altitude, latitude and longitude (difference of local time) reflect on δT fields in the lowermost layer. The zone of the minimum $|\delta T_{SFC}|$ extends approximately along the path of the cloud cluster, which is along the S-frontal zone

Fig. 16 Fields of mean difference temperature at 850 mb δT_{850} and at surface δT_{SFC} . Black triangles present 12-hourly location of the cloud cluster in the analysis period.

Fig. 17 Fields of mean difference height at 850 mb δZ_{850} and mean difference wind at 850 mb δV_{850} .

over the Continent. Since the zone of the minimum $|\delta T_{SFC}|$ seems also to be along the Chang Jiang basin, the influence of the low and wet land along the basin on δT_{SFC} (small temperature change) is also suggested. The zone of the minimum $|\delta T_{850}|$ approximately coincides with the zone of the minimum $|\delta Z_{850}|$ (see the isoline of δZ_{850} at the eastern foot of the Tibetan Plateau). It is also seen that δV_{850} is small along the path of the cloud cluster. On the contrary, δT_{850} and δV_{850} are large over the Continent south of the S-frontal zone. It is notable that δV_{850} of ~ 5 m/sec is directed eastward from the Continent to the Pacific. The southern area of the Continent is a plateau of about 500 m in altitude on the average, and fine weather continued there throughout the analysis period. The insolation heating and the nocturnal radiative cooling in the high land area under clear sky condition will result in large δT_{850} and δV_{850} . Horizontal "shear" between small δV_{850} at the north side of the frontal zone and large δV_{850} over the

Fig. 18 Fields of $\delta \zeta_{850}$ (vorticity) and of $\delta(\theta_{500} - \theta_{850})$. Stippled areas present areas of $\delta \zeta_{850}$ more than $4 \times 10^{-6} \text{ sec}^{-1}$. Hatched areas present areas of $\delta(\theta_{500} - \theta_{850})$ below -1°K .

southern Continent and the Pacific results in large positive $\delta \zeta_{850}$ in the frontal zone (Fig. 18). At the same time the air in the frontal zone over the Continent becomes thermally more unstable at 00GMT (see negative area of $\delta(\theta_{500} - \theta_{850})$ in Fig. 18). Such large-scale dynamic and thermodynamic changes of the frontal zone at night-to-morning will activate convections in the cluster in morning, which propagates in the frontal zone. The mean difference field of vorticity at 500 mb $\delta \zeta_{500}$ also indicates that the medium-scale circulation associated with the cluster was more enhanced at 00GMT than 12GMT.

The author does not know the exact mechanism of this periodic variation of convections in the present case. However, similar phenomena have been reported by several authors. Diurnal variation in rainfalls, thunderstorms, cloud coverage and/or deep convective cloud systems has been studied by many authors

(e.g., Wallace, 1975; Weickmann *et al.*, 1977; Gray and Jacobson, 1977; Murakami, 1979). In these studies, various mechanisms of the diurnal variation have been proposed to explain complicated patterns of the diurnal variation in convective activity. Radiational difference between cloud-free surrounding and cloud-covered area as pointed out by Gray and Jacobson (1977), will also contribute to development of the present cloud cluster in 03LST–09LST (18GMT–00GMT), though the effect cannot be evaluated separately.

10. Concluding remarks

A long-lived medium-scale cloud cluster over the subtropical East Asia in a Baiu season has been analyzed on its evolution process, variations in convective activity, mesoscale fine structure and associated disturbance. The author's attention has been focused on differences in environmental situation and cloud/rainfall features of the cluster between over the Continental China region and over the Japan Islands. The results of the analysis are as follows:

1). In the earlier period of the evolution over the Continent, the cloud cluster propagated accompanying with a core of weak cyclonic vorticity in the southern frontal zone. In the latter period, during which the cluster passed over the Japan Islands and the Pacific, the cloud cluster developed into a frontal depression coupled with an upper short wave trough in the baroclinic zone. This change from the vorticity core in the southern frontal zone to the short wave trough will explain the long life time of this small-scale (~ 1000 km) cloud cluster.

2). The features of cloud, echo and rainfall in the cluster were changed in evolution process with changes of its associated disturbance and environmental situation. That is, the cluster developed in the tropical unstable air over the Continent was mainly formed by convective cloud (of T_{BB} lower than -40°C), while the cluster developed in the subtropical baroclinic zone over the Japan Islands was formed by both convective and stratiform clouds. The stratiform clouds spreading in the north and east of the cluster brought about

continuous rainfall (1–10 mm in one hour) and was not accompanied with thunderstorms.

3). The cloud cluster in the earlier period shrunk after heavy rainfalls. On the other hand, in the latter period the cluster developed after heavy rainfalls. This fact implies that the development of the cluster and/or the associated depression is not necessarily related directly to occurrence of heavy rainfalls. The baroclinicity of the atmosphere is thought to be an important factor for the development of medium-scale disturbances in the Baiu front.

4). The cluster consists of a few mesoscale cloud cells, and the cell further consists of several convective cores. This fine structure in the cluster was commonly found over the Continent and the Japan Islands, though environmental situations and associated disturbances were different between the two regions. The periodic variation of several-hour period in convective activity within the cluster was due to alternate development of mesoscale cells in the cluster.

5). In macroscopic (medium-scale), precipitation features in the cloud cluster over the Japan Islands revealed by PPI radar observation coincide with cloud features of the cluster on satellite images and/or T_{BB} maps. However, in microscopic (mesoscale), precipitation features were significantly different from cloud features.

6). Variation of convective activity within the cloud cluster of about one day period was deeply related to large-scale change in the thermal and wind fields.

On the whole, when the present cluster was located over the Japan Islands, it showed common features to medium-scale cloud clusters frequently observed in the Baiu front over the Japan Islands, which have been investigated in the previous studies (e.g., Akiyama, 1978, 1979; Ninomiya and Akiyama, 1971).

At the end of this chapter, the present cloud cluster located over the Continent is to be compared with MCC in USA, though the description on MCC by Maddox (1980) is morphological and does not show evidently the dynamic structure of MCC. The cloud feature (configuration) on IR images resembles each other, though the size of MCC is relatively

large. In comparison of the present cluster with the MCC of Bosart and Sanders (1981), the variation of about one day period in convective activity or rainfall and the development in a non-baroclinic zone are pointed out as common features.

Thermal, kinematic fields and heat budget around the present cluster will be investigated in Part II of the present paper.

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梅雨前線上の中間規模雲 cluster

第 I 部 発達過程と微細構造

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梅雨期に、中国大陸上で発生し、日本列島上へ移動した中間規模 (～1000 km) 雲 cluster の case study をおこなう。

Part I で、この雲 cluster の雲降水の様相、cluster 周辺部の総観場の特徴および cluster の発達に関連している擾乱系を、GMS, Radar, および FGGE data によって解析する。

cluster は、1979年7月12日に、チベット高原東端で発生し、～30N 緯度線に沿い、～1000 km/day の速度で、東方へ移動した。発生から2日後、九州に大雨を降らせ、その後、梅雨前線上の frontal depression へと発達した。cluster は、中間規模の雲域を約3日間維持していた。cluster の発達過程を、formation, developing, transitional および cyclone-formation stages の4段階にわけ解析を行った。以下に結果を要約する。

1. 中国大陸 (formation, developing stages) で、cluster は GMS 画像上、楕円形の孤立した雲分布をしており、大陸の南側の中層強風帯 (southern frontal zone) 上の小規模の弱い正渦度 core に伴って、発達した。小規模の正渦度 core は、チベット高原による lee-cyclogenesis によって発生したものであろう。

2. 日本列島～太平洋上 (cyclone-formation stage) では、cluster は elongated cloud system となった。大陸の北側強風帯 (northern frontal zone) を移動して来た short wave trough の影響下で、frontal depression に伴う大規模な雲 system へと発達する過程にある。

3. cluster の雲・降水の様相は、発達過程の前半 (大陸上) と後半 (日本列島上) で大きく異なる。大陸の不安定かつ一様な熱帯性の大気中で発達した cluster は、対流雲 (Cb) のみから形成され、一方、傾圧帯 (日本列島上の梅雨前線) で発達した cluster は、対流雲 (対流エコー) および層状雲 (層状エコー) から形成されている。

4. cluster の降水は、developing stage の末期に極大に達し、中層の正渦 core は消失した。その後、雲域も縮小した。cyclone-formation stage に、cluster の降水は再度極大に達した。その後、cluster は frontal depression へと発達した。

5. cluster は、その発達過程で、しばしば mesoscale (～100 km) の cell 状微細構造を示す。cell 中心部の T_{BB} は $\sim -70^{\circ}\text{C}$ (雲頂高度にして約 16 km) である。

6. cluster の雲域の広がり、および極小 T_{BB} 値は、発達過程をとおして、数時間周期の時間変動を示す。この変動は、cluster 内の mesoscale cells の発達衰弱による。

7. 日本列島上の cluster の radar echo 分布と、GMS T_{BB} 分布との対比を行った。巨視的には、両者はよく対応する。しかし cluster の微細構造である mesoscale cell 状雲分布と、mesoscale echo systems との対応関係は、それらの発達期と衰弱期とでは、異なる。

8. T_{BB} map 上の cluster は、約一日周期の変動 (早朝の発達・昼間の衰弱) をも示す。この変動は、12GMT に比し 00GMT に、大規模的な frontal zone の強化 (正渦度と不安定度の増加) がひきおこされていることに関連している。

以上の結果から、中間規模雲 cluster の長命は、その発達過程で、擾乱系の交代していたことによること、大陸上と日本列島上では、cluster の発達した前線の構造、cluster に伴った擾乱および雲降水の特性に大きな違いがあるにもかかわらず、cluster の mesoscale 的な微細構造は、両域に共通してみられたこと、が結論として指摘される。