A Medium-Scale Cloud Cluster in a Baiu Front

Part II: Thermal and Kinematic Fields and Heat Budget

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Abstract

Observation features and evolution process of a long-lived medium-scale cloud cluster have been analyzed in Part I of the present paper. Thermal and kinematic fields and heat budget of this cloud cluster are investigated in Part II. The special attention is given in its formation and developing stages over the Continental China region.

The following results were obtained.

1). A cloud cluster developed in the uniform unstable tropical air over the Continent. Thermal fields in and around the cloud cluster exhibited local variations due to convections and 3-dimensional moisture advection.

2). Kinematic fields in the cloud cluster over the Continent also showed particular localized features. That is, medium-scale cyclonic circulation in the lower troposphere, anticyclonic circulation in the upper layer and upward motion are found. They indicated time variations throughout the formation and developing stages.

3). An apparent moisture sink in the lower troposphere and an apparent heat source in the upper troposphere existed in the cloud cluster. The both quantities reached the maxima at the time when observed rainfall reached the maximum (~80 mm/6 hour).

4). Calculated rainfall (vertically integrated apparent moisture sink) showed similar time variation to that in the observed rainfall: The calculated rainfall amount showed a variation of about one day period, that was consistent with the observed variation analyzed in Part I of the present paper.

5). Thermal and kinematic fields in and around the cloud cluster investigated in this study, which developed in the uniform unstable air over the Continent, showed similar features to those of medium-scale cloud clusters frequently developed in the Baiu front (subtropical baroclinic zone) over the Japan Islands and the Pacific Ocean, in spite of different environmental situations.

The present study indicates that the cloud cluster transformed into a frontal depression under the influence of a short wave trough in the subtropical baroclinic zone. It is conjectured that in the atmosphere without baroclinicity the cloud cluster remained as a cloud cluster without transforming into a depression, even though a large amount of heat was released and redistributed through convections.

1. Introduction

Thermal and kinematic structures and heat and moisture budgets of convective cloud systems have been studied by several authors. For examples, Cb cloud systems developed in tropical oceanic areas have been studied by Ruprecht and Gray (1976a and b) and Ogura et al. (1979).

While a particular kind of Cb cloud systems named “mesoscale convective complex” (Maddox, 1980) which develops in middle latitudes of USA has been examined by Bosart and Sanders (1981).

Medium-scale convective systems are frequently observed also in the Baiu frontal zone. The evolution process, thermodynamic and
kinematic features of these systems and associated medium-scale disturbances over the Japan Islands have been investigated (e.g., Akiyama, 1979; Ninomiya and Akiyama, 1971, 1972, 1973; Yoshizumi, 1977a, b; Ninomiya and Yamazaki, 1979). These studies, however, are limited to the analysis of disturbances in the eastern portion of the Baiu front (i.e., over the Japan Islands and the Pacific area). Recently, it was revealed that some of the disturbances have their origin in the Continental China region and are propagated to Japan (Narikawa, 1980; Ninomiya et al., 1981). These studies, however, are very brief observational documentations. To understand further the organized convective systems in the subtropical East Asia in the Baiu season, the analysis covering the whole evolution process from their initial formation over the Continent to their development into frontal depressions over the Pacific region is needed.

The subject has been already discussed in a companion paper (Part I), concerning the evolution process of a cloud cluster, disturbances, cloud and rainfalls, thunderstorms, mesoscale fine structure and periodic variations of convective activity in the cloud cluster, based on GMS IR pixel data, upper air and surface data, and radar data for the whole evolution process from its generation over the Continent to development into a large cloud system of a frontal depression over the Pacific Ocean.

The purpose of this paper (Part II) is to describe thermal and kinematic fields, heat and moisture budgets of the cloud cluster in the formation and developing stages (i.e., the cloud cluster located over the Continent) and to compare them with those in the cyclone-formation stage of the cloud cluster (i.e., the cloud cluster located over the Japan Islands) as well as with the results of the aforementioned papers.

2. Outline of the evolution of the cloud cluster

In this section, the features and the evolution of the cloud cluster analyzed in Part I of the present paper are summarized.

In the formation and developing stages (12GMT, 12 July~00GMT, 14 July, 1979), the cloud cluster was located over the Continental China region. As shown in Fig. 1, the cloud cluster was generated at the eastern foot of the Tibetan Plateau at ~12GMT, 12 July and propagated eastward with a phase speed of ~1000 km/day, maintaining its medium-scale cold cloud area ($T_{BB}$ lower than $-40^\circ$C). Over the Continent, the cloud cluster moved along the southern frontal zone (S-frontal zone), which was extending along ~30N latitude circle and characterized by strong low-level winds and weak horizontal temperature gradient. The cloud cluster was accompanied with a weak positive vorticity core in the middle layer (Fig. 2), which was thought to be a lee-cyclone of the Tibetan Plateau and propagated along the frontal zone. The magnitude of the vorticity reached the maximum at ~12GMT, 13 July (one day after its generation). However, the vorticity core became obscure in the following 12 hours (12GMT, 13~00GMT, 14) around the east coast of the

![Fig. 1 Observation stations and network of subdomains used for budget calculation. Shaded areas are 12-hourly locations of cloud areas of the cloud cluster, in which $T_{BB}$ is lower than $-40^\circ$C.](image)

![Fig. 2 Movement of cores of the maximum positive vorticity for the analysis period (12GMT, 12~12GMT, 15 July 1979). Black triangles present 12-hourly locations of the cloud cluster.](image)
Continental. After 00GMT 14, the cloud area (area of $T_{BB}$ lower than $-40^\circ$C) of the cluster began to shrink. In these stages, the cloud cluster was composed of mainly convective clouds.

In the transitional and cyclone-formation stages (00GMT 14~06GMT 15 July), the cloud cluster moved from the East China Sea to the Japan Islands, and came under the influence of a short wave trough which was propagated from the northern frontal zone (N-frontal zone) to the baroclinic zone (Baiu front over the Japan Islands). In these stages, the oval-shaped cloud cluster changed into a large cloud system accompanying a frontal depression. In these stages the cloud cluster was composed of both convective and stratiform clouds.

3. Thermal situation

a. Large-scale feature

The horizontal gradient of $\theta_{e500}$ attains maximum at 35~40N latitude zone throughout the analysis period (Fig. 3). The zone of maximum $\nabla \theta_{e500}$ over the Continent extends along the south side of the 300 mb jet axis (subtropical jet). The large gradient of $\theta_{e500}$ in this region is not due to gradient of temperature, but to that of mixing ratio, while the large horizontal gradient of $\theta_{e500}$ over the Japan Islands to the Pacific Ocean is due to gradients of both temperature and mixing ratio. To the south of the zone of maximum $\nabla \theta_{e500}$, a region of high $\theta_{e500}$ (>$346^\circ$K) spreads from the south China to the Pacific. This high

![Fig. 3](image_url)
\( \theta_{\text{e850}} \) region is horizontally uniform in \( \theta_e \) and has potential instability in the 850-500 mb layer.

As seen in Fig. 3, the cloud cluster developed in this horizontally uniform unstable air over the Continent, while over the Japan Islands and the Pacific Ocean it developed within the zone of maximum \( \theta_{\text{e850}} \) (baroclinic zone) in association with an upper-level short wave trough.

Over the southern Continental region, there are localized areas of extremely high \( \theta_{\text{e850}} \) (>352°K) in the high \( \theta_{\text{e850}} \) region. These areas are characterized by high mixing ratio. The cloud cluster was located to the north side of the extremely high \( \theta_{\text{e850}} \) (>352°K) areas, associating with a core of the maximum upward motion\(^\dagger\). The maximum upward motion there was \(-3\) mb/h at 12GMT 12, \(-18\) mb/h at 12GMT 13, and \(-9\) mb/h at 00GMT 14 July, respectively. Around the cloud cluster, the potential instability tends to diminish.

Over the Japan Islands and the Pacific region, the cloud cluster moved along the subtropical baroclinic zone, along the northern rim of the high \( \theta_{\text{e850}} \) region. The moist neutral layer appeared in and around the cloud cluster. The air in the lower layer to the south of the frontal zone (Pacific area) is potentially unstable and has higher relative humidity ((\( T - T_d \))\text{SFC}=\sim-3^\circ \text{C}, Fig. 4) than that over the southern Continental region. However, convective clouds did not develop over this high \( \theta_{\text{e850}} \) region, because subsidence in the Pacific anticyclone suppressed development of deep convections.

b. Static stability in and around the cloud cluster

The vertical profiles of potential temperature \( \theta \), equivalent potential temperature \( \theta_e \) and saturated equivalent potential temperature \( \theta_e^* \) in and around the cloud cluster are presented in Figs. 5-a, -b and -c. Figs. 5-a and -b are for the developing stage (over the Continent), while Fig. 5-c is for the cyclone-formation stage (over the Japan Islands). The profiles in Fig. 5 suggest that local variations of thermodynamic quantities which are connected with the presence of the cluster are superimposed on large-scale fields. Characteristic features of the profiles are as follows:

**Developing stage**

The profiles of \( \theta \) or \( \theta_e^* \) above 850 mb at the stations in Figs. 5-a and -b are more or less similar to each other, while the profiles of \( \theta_e \) show local variation due to difference in mixing ratio. The 850-500 mb layer at the stations 58424 (Fig. 5-a) and 58367 (Fig. 5-b), which are located to the east side and the south side of the cluster, respectively, i.e., the low-level inflow side of the cloud cluster, is potentially unstable (\( \Delta \theta_e / \Delta p = \sim 3.5^\circ \text{K/100 mb} \)), but \( \theta_{\text{e850}} \) does not much exceed \( \theta_{\text{e500}} \) (\( \Delta \theta_{\text{e850}} - \theta_{\text{e500}} / \Delta p = \sim 0^\circ \text{K/100 mb} \)). At these stations relative humidity is relatively low, while potential temperature is very high in the lower layer. Therefore \( \theta_e^* - \theta_e \) in the lowest layer is as large as \( \sim 20^\circ \text{K} \).

On the other hand, the 850-500 mb layer at the stations 58203 (Fig. 5-a) and 58238 (Fig. 5-b), which are located within the cloud cluster, is less potentially unstable, \( \Delta \theta_e / \Delta p = \sim 2.5^\circ \text{K/100 mb} \), but \( \theta_{\text{e850}} \) exceeds \( \theta_{\text{e500}} \) (\( \Delta \theta_{\text{e850}} - \theta_{\text{e500}} / \Delta p = \sim 2.5^\circ \text{K/100 mb} \)) and \( \theta_e^* - \theta_e \) in the lowest layer is small. This difference in thermal properties between the low-level air at the inflow side of the cloud cluster, which has strong potential instability, relatively low humidity and very high temperature, and the air in the cluster, which has large instability

\(^\dagger\) The vertical \( \rho \)-velocity at 700 mb, \( \omega_{700} \) of the initial field of Northern Hemispheric Prediction Model of JMA. The figures are not presented here.
Fig. 5-a Vertical profiles of potential temperature, $\theta$ equivalent potential temperature, $\theta_e$ and saturated equivalent potential temperature, $\theta_{es}$ at stations located in and around the cloud cluster at 12GMT, 13 July. The cold cloud areas ($T_{BB} < -40^\circ$) of the cloud cluster are depicted by $T_{BB}$ isotherms of $-10^\circ$ intervals. Wind barbs are presented by conventional notation (knots).

Fig. 5-b The same as Fig. 5-a, but at 00GMT, 14 July.
(\theta_{e850} > \theta_{e500}) and high relative humidity (see the area of instability in Fig. 10), will be explained from the upward motion in the cluster (see the vertical \(p\)-velocity in Fig. 9) and horizontal advection of \(\theta_e\). The process of the change in thermal properties, however, cannot be quantitatively described, because of insufficient density of observations.

The sounding in the cloud cluster is not necessarily the sounding in a Cb within the cluster: The dimension of the updraft core of Cb is much smaller than that of the cluster. None of soundings in Figs. 5-a, 5-b and 5-c is considered as the sounding inside of Cb. The analysis based on the satellite IR (\(T_{BB}\)) observations (see Part I of the present paper) revealed that the top of Cb within the cluster reached up to 200~150 mb or even the tropopause. The \(\theta_e\) and \(\theta_e^*\) at 200 mb over the Continent is \(\sim 360\)K. The air having such high \(\theta_e\) (\(\sim 360\)K) is found only in the lower layer (850~950 mb) in the cloud cluster and/or in the inflow area of the cluster. The heights of the base of cumulonimbus and/or cumulus congestus within the cluster, which are reported in the international synoptic code, are given in Table 1. Over the Continent, the height of the base of the active convective cloud within the cluster is 600~1500 m on the average. This indicates that the low-level air in the cluster and/or in the inflow area of the cluster reaches to the higher level (200~150 mb) as the updraft in Cb, though the sounding in such updraft is not observed by the upper air observations used in the present analysis.

A nearly neutral layer, \(\Delta \theta_e / \Delta p = \sim 0\)K/100 mb is found in the middle level to the north and west sides of the cloud cluster (57178 of Fig. 5-a and 58150 of Fig. 5-b), but the relative humidity is relatively low. These stations

<table>
<thead>
<tr>
<th>Date</th>
<th>Place (over)</th>
<th>Observed height of cloud base</th>
</tr>
</thead>
<tbody>
<tr>
<td>12GMT 12 July 1979</td>
<td>Continent</td>
<td>600~1500 m</td>
</tr>
<tr>
<td>00GMT 13</td>
<td>Continent</td>
<td>1500~2000 m</td>
</tr>
<tr>
<td>12GMT 13</td>
<td>Continent</td>
<td>600~1500 m</td>
</tr>
<tr>
<td>00GMT 14</td>
<td>Continent</td>
<td>1000~1500 m</td>
</tr>
<tr>
<td>12GMT 14</td>
<td>Sea</td>
<td>600~1000 m</td>
</tr>
<tr>
<td>00GMT 15</td>
<td>Sea</td>
<td>300~1000 m</td>
</tr>
</tbody>
</table>
are located at the region of downward motion of the cloud cluster (Fig. 9). The dry and nearly neutral layer is considered to result from horizontal and vertical advections of $\theta_e$.

In the special observations over the Japan Islands, it was frequently observed that the saturated neutral layer exists in the area of active convection, which may be a result of convective mixing (Akiyama, 1979; Ninomiya and Yamazaki, 1979). In the present case, however, such moist neutral layer is not found within the cloud cluster. This may be due to insufficient density of observations in space and time.

**Cyclone-formation stage**

Because the cloud cluster was located in the subtropical baroclinic zone over the oceanic area, profiles of $\theta$, $\theta_e$, and $\theta_e^*$ around the cloud cluster are significantly different from those over the Continent. The air in the lowest layer over the ocean is very moist and $(\theta_e^* - \theta_e)$ in the layer is small (47827 in Fig. 5-c). The dryness in the 800–500 mb layer at 47909 is due to the large-scale subsidence above the inversion in the subtropical anticyclone, while the dry air in the 900–700 mb layer at 47807, which is located just behind the cloud cluster, may be due to the medium-scale downward motion compensating the strong upward motion in the cluster.

The features of instability in and around the cloud cluster over the oceanic area, i.e., the potentially unstable layer ($\Delta \theta_e^*/\Delta p > 0 \text{K}/100 \text{mb}$) in the east to south sector and the relatively stable layer ($\Delta \theta_e/\Delta p \approx 0 \text{K}/100 \text{mb}$) behind the cluster, are similar to those when the cloud cluster was over the Continent, in spite of the differences in environmental situations. This indicates that the vertical motion in the cluster, rather than the environmental situations (such as continental or oceanic environment), is the crucial factor to determine the thermodynamic quantities of the cloud cluster.

4. Wind fields

In this section, medium-scale features of

† Severe Rainstorms Research Project was conducted by the Japan Meteorological Agency in the Baiu seasons of 1968–1971.

the wind field in the vicinity of the cloud cluster will be described. Sequential maps of the wind fields at 850, 500 and 200 mb levels at 12 hour interval are presented in Figs. 6, 7 and 8. The 850 mb wind field indicates the low-level inflow into the cloud cluster, while the 200 mb wind field indicates the feature of outflow. The 500 mb wind indicates the circulation system in the middle troposphere of the cloud cluster.

850 mb

In the formation and developing stages, the cloud cluster was located at the north side of the southern maximum wind zone, where horizontal wind shear is strong. Although the flow with large cyclonic curvature is not found around the cluster, locally enhanced strong SSW–WSW winds converged toward the cluster and resulted in a medium-scale convergence field in the cluster. The wind fields at the cyclone-formation stage (12GMT, 14 July) show also similar feature to that described above.

500 mb

The cloud cluster was located in the north side of the southern maximum wind zone of 500 mb level in the formation and developing stages (12GMT 12–00GMT 14). The maximum wind zone is evidently seen at 12GMT 12 and 00GMT 13. It became, however, gradually obscure to the end of the developing stage (00GMT 14). The flow with cyclonic curvature associated with the cluster is most evident in the wind fields of Fig. 7 at 12GMT 13, when the positive vorticity reached the maximum (Fig. 2).

At 12GMT 13, the northern maximum wind zone existed about 800 km to the north of the cluster. Then the zone shifted southward to form a confluence zone with the southern strong wind zone. At 00GMT 14, therefore, wind speed around the cluster and to the north side of it was almost uniform and the cyclonic curvature of the flow around the cluster became weak, i.e., the middle-level medium-scale cyclonic circulation system associated with the cloud cluster over the Continent tended to decay. At the beginning of the cyclone-formation stage, localized cyclonic wind shear was obscure still at 500 mb level. In the fol-
Fig. 6 Sequential maps of wind vector fields at 850 mb at 12-hourly. Numerals beside stations are wind direction (deg) and wind speed (m/s). The cloud areas ($T_{BB}<-40^\circ$C) are depicted by $T_{BB}$ isotherms with intervals of $-10^\circ$C. Black areas in the cloud areas show the cold area of $T_{BB}<-70^\circ$C.

Following several hours, a frontal depression was formed in the subtropical baroclinic zone (the eastern portion of the Baiu front), as an upper-level short wave trough approached the cluster.

**200 mb**

During the earlier period, the upper-level jet (subtropical jet) exists far north of the cloud cluster and seems to have no direct influence on it. After this period, the cloud cluster gradually approaches the upper-level jet. In the cyclone-formation stage (12GMT 13 in Fig. 8), the jet axis is located about 300 km north of the cluster.

There was localized strong wind at the north and northeast sides of the cluster throughout the analysis period. At the north side, the wind speed, especially southerly component is large, while relatively weak wind is found at the south edge of the cluster in 12GMT 13~12GMT 14. These winds form localized anticyclonic and divergence fields on the cloud cluster. Similar features, *i.e.*, strong north side winds and outflow (anticyclonic, diffuent and divergent flow) were found in thunderstorm areas in USA. (Ninomiya, 1971;
5. Vorticity and divergence fields and structure of disturbance

Vorticity and divergence fields of medium-scale cloud clusters developed in Baiu fronts over the Japan Islands have been studied by several authors (e.g., Ninomiya and Akiyama, 1971; Yoshizumi, 1977a). The detailed analysis for the cyclone-formation stage of the present cluster was not made because the cloud cluster did not pass over the center of the observation network of Japan. It is supposed that it possessed common properties to similar disturbances already studied. Thus the present investigation is confined to the formation and developing stages during which the cloud cluster was situated over the Continent. Divergence \( \text{DIV} \), vorticity \( \zeta \) and vertical \( p \)-velocity \( \omega \) were evaluated on each subdomain enclosed by aerological stations as shown in Fig. 1. The dimensions of these subdomains are listed in Table 2. Divergence and vorticity were calculated on the mandatory pressure levels, and vertical \( p \)-velocity was evaluated by the vertical integration of the divergence utilizing the continuity equation. Thus obtained \( \omega \) does not always vanish at the top of the atmosphere, therefore, \( \omega \) was corrected linearly in the 500-100 mb layer assuming that \( \omega = 0 \) at 100 mb, as proposed by O'Brien (1970). Fig. 9 shows divergence, vertical \( p \)-velocity and vorticity fields...
in the cloud cluster at 12GMT 13 July, when the middle-level positive vorticity core associated with the cloud cluster was most evident. Height, temperature and stability fields at the same time are also presented in Fig. 10. Figs. 11 and 12 show vertical profiles of $\zeta$, DIV and $\omega$ in a certain subdomain around the cloud cluster at 12-hour intervals.

**a. Vorticity**

At 12GMT 13, there is a medium-scale core of positive vorticity at the west side of the cloud cluster. The maxima are $\sim 8 \times 10^{-5} \text{sec}^{-1}$ at 500 mb and $\sim 3 \times 10^{-6} \text{sec}^{-1}$ at 850 mb, respectively. The cyclonic circulation associated with the cluster is most intensive at the middle level and the axis of the circulation system is slightly tilted to the west with height. At the 200 mb level, a medium-scale anticyclonic circulation with vorticity of $\sim -10 \times 10^{-6} \text{sec}^{-1}$ is formed over the cluster. This upper anticyclone was formed in association with the upper outflow of the cluster.

Next, time variation in medium-scale vorticity field is examined. Fig. 11 shows sequential vertical profiles of vorticity in the west and east sides of the cluster at 12-hour intervals.

The maximum of $\zeta$ is $8 \times 10^{-5} \text{sec}^{-1}$ over the subdomain of $\sim 3.4 \times 10^4 \text{km}^2$, while the grid point ($\sim 380 \text{km grid distance}$) value of $\zeta$ is $13 \times 10^{-6} \text{sec}^{-1}$ at 12GMT 13 (Fig. 2). The latter was obtained from much smoothed wind field.
Table 2 Dimensions of subdomains in which the budget calculations are performed.

<table>
<thead>
<tr>
<th>Subdomain</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$8.84 \times 10^4$ km$^2$</td>
</tr>
<tr>
<td>D</td>
<td>8.30</td>
</tr>
<tr>
<td>E</td>
<td>6.79</td>
</tr>
<tr>
<td>F</td>
<td>3.73</td>
</tr>
<tr>
<td>G</td>
<td>4.00</td>
</tr>
<tr>
<td>H</td>
<td>3.70</td>
</tr>
<tr>
<td>I</td>
<td>3.17</td>
</tr>
<tr>
<td>J</td>
<td>3.93</td>
</tr>
<tr>
<td>K</td>
<td>2.88</td>
</tr>
<tr>
<td>L</td>
<td>4.93</td>
</tr>
<tr>
<td>M</td>
<td>6.44</td>
</tr>
<tr>
<td>N</td>
<td>4.55</td>
</tr>
<tr>
<td>O</td>
<td>5.44</td>
</tr>
<tr>
<td>P</td>
<td>5.30</td>
</tr>
<tr>
<td>Q</td>
<td>3.55</td>
</tr>
<tr>
<td>R</td>
<td>2.99</td>
</tr>
<tr>
<td>W</td>
<td>2.86</td>
</tr>
<tr>
<td>X</td>
<td>2.78</td>
</tr>
<tr>
<td>Y</td>
<td>3.08</td>
</tr>
</tbody>
</table>

Throughout the formation and developing stages spatial pattern of the vorticity did not change greatly. That is, there is low-level positive vorticity in the cluster and middle-level positive vorticity in the west side of the cluster. The former reaches the maximum intensity at 00GMT 14, while the latter reaches the maximum at 12GMT 13. As stressed in Part I of the present paper, the most intense rain of the cluster in the developing stage occurred around 00GMT 14, when the middle-level cyclonic vorticity began to weaken. At the same time, the cloud area (area of $T_{BB} < -40^\circ$C) of the cluster began to shrink. The upper-level anticyclonic vorticity is also found throughout the analysis period, which is the maximum at $\sim 200$ mb.

The feature of vorticity field of the cluster in the cyclone-formation stage (18GMT 14) is somewhat different from that over the Continent. In the cyclone-formation stage, vorticity profile in the west side of the cluster is almost the same as that in the east side. In the both sides, positive vorticity is large in the lower layer (1000–800 mb) and is small in the middle layer. At 18GMT 14, the middle-level cyclonic vorticity core of the short wave trough (Fig. 9) is.
Fig. 10 Temperature and height fields of the cloud cluster at 12GMT, 13 July 1979. The right figure shows stability. Stipples indicate unstable area, \((\theta_{e850} - \theta_{e500}) / \Delta p > 0K/100mb\). The analyzed octagonal area is the same as Fig. 9.

Fig. 11 Vertical profiles of vorticity, \(\zeta\) on sub-domains located at the west side (upper figure) and at the east side (lower figure) of the cloud cluster. The locations of subdomains are presented in Fig. 1.

2), which is approaching the cloud cluster from the northwest, is about 600 km apart from the cluster still. However, the low-level cyclonic vorticity is already formed at the center of the cluster. These features are commonly found for medium-scale disturbances in the depression-formation process in the Baiu front over the Japan Islands.

b. Divergence and vertical \(p\)-velocity

It is a common feature found throughout the analysis period, that the level of the maximum convergence shifts to north with height (Figs. 9 and 12). That is, in the southeast side of the cluster, convergence is large at the 850 mb level, while in the northwest side of the cluster, convergence is large at the 700 mb level. Consequently, an area of strong upward motion at 500 mb is formed within the cluster. The air flowing from south and east to the cloud cluster is lifted within the cluster. The core of upward velocity is located in the east side (ahead) of the positive vorticity core. The maximum upward motion is \(-40\sim-60\) mb/hour. Strong upper-level divergence covers the cluster, and the position of the divergence center agrees with the core of the upward motion. This upper-level divergence is due to the outflow from the top of the cluster. The magnitude of divergence is larger than that of low-level convergence, and the layer of outflow is restricted to a thin layer around the cloud top. The maximum low-level convergence and upward motion in the formation and developing stages of the cluster are \(\sim -5 \times 10^{-5}\) sec\(^{-1}\) and \(\sim -60\) mb/hour, respectively. This maximum values were observed at 00GMT 14, when rainfall attained \(\sim 80\) mm in 6 hours.

c. Temperature and height fields

Temperature and height fields are examined at 12GMT 13 (Fig. 10), when the cyclonic
vorticity in the middle layer attained the maximum. A medium-scale cold low or trough is found just north of the positive vorticity core throughout the whole troposphere. The amplitude of the disturbance in height is \(\sim 20\) gpm at 700 mb and \(\sim 50\) gpm above 500 mb, respectively. Comparing with temperature in environment, the temperature in the cloud cluster is low by about 2°C in the lower troposphere (\(\sim 700\) mb), while the temperature is high by about 2°C in the upper troposphere (400\(\sim 200\) mb). The maximum amplitudes of the disturbance in height and temperature was observed at 12GMT 13. At present, the mechanism of the cold-core formation is not known. The cooling due to evaporation from precipitating particles may be one of the mechanisms.

6. Heat and moisture budgets

In this section, heat and moisture budgets of the cloud cluster are analyzed using the upper air observation data, which obtained at 12-hour time interval and \(\sim 300\) km spatial interval. Because the horizontal dimension of the cluster is \(\sim 300\) km and its propagating speed is \(\sim 1000\) km/day, the precise evaluation of each term in the budget equations will be difficult. Even if some errors in quantitative analysis are unavoidable, the examination on the heat and moisture budget situations of the cloud cluster and the time change in the budget situation would be still useful to understand the nature of the cluster. The apparent heat source \(Q_1\) and apparent moisture source \(Q_2\) in the cloud cluster over the Continent are evaluated and their time variations are described. \(Q_1\) and \(Q_2\) are expressed as

\[
Q_1 = \frac{\partial T}{\partial t} + \nabla \cdot \vec{V} T + \frac{\partial \omega T}{\partial p} - \frac{R}{C_p} \frac{\omega F}{p}
\]

\[
Q_2 = L \left( \frac{\omega q}{C_p} + \nabla \cdot \vec{V} q + \frac{\partial \omega q}{\partial p} \right)
\]

where notations are conventional and bar indicates areal mean. The corrected value of vertical \(p\)-velocity, \(\omega\) (see section 5) is used for the evaluation. Local time change was calculated for 24 hours centered at the observation time. Calculation was made at the mandatory pressure levels for subdomains shown in Fig.

![Fig. 13](https://via.placeholder.com/150)

1. Typical profiles of \(Q_1\) and \(Q_2\) at the different evolution stages of the cloud cluster are presented in Fig. 13.

Thermodynamic eq. and continuity eq. of moisture are expressed as follows:

\[
Q_1 + \frac{\partial \omega T}{\partial p} = \frac{L}{C_p} m - Q_R
\]

\[
\frac{C_p}{L} Q_2 + \frac{\partial \omega q}{\partial p} = -m
\]

where \(m\) is amount of condensed water vapor in unit air mass per unit time. The vertical convergence of convective transfer of total heat energy \((Q_1 + Q_2) = -\frac{\partial}{\partial p} \left( \omega T' + \frac{L}{C_p} \omega q' \right)\) was obtained from (3) + \(\frac{L}{C_p} \times (4)\), neglecting radiation term, \(Q_R\). Profiles of \((Q_1 + Q_2)\) are also presented in Fig. 13.

There are apparent heat source \(Q_1\) and apparent moisture sink \(Q_2\) throughout the period. The maximum absolute values of \(Q_1\) and \(Q_2\) increase from \(\sim \pm 1\) K/h at 12GMT 12 to \(\sim \pm 5\) K/h at 00GMT 14. The vertical pro-
files of \((Q_1+Q_2)\) are characterized by apparent sink in the lower troposphere and apparent source in the upper troposphere. The maximum total heat energy sink of \(\sim -3\text{K/h}\) in the 850-700 mb layer and source of \(\sim +2\text{K/h}\) in the 500-400 mb layer are observed at 00GMT 14, around which the cloud cluster brought about the maximum areal-averaged rainfall (see Table 4).

Eq. (4) is integrated from the top of the troposphere to the surface,

\[
-\int_{P_{top}}^{P_{SFC}} \frac{d\rho}{m} = \frac{C_p}{L} \int_{P_{top}}^{P_{SFC}} Q_2 \, \frac{d\rho}{g} + \left(\omega \frac{q}{g}\right)_{SFC}
\]

where left hand term is amount of condensed moisture in unit air column, the first term of right hand is apparent moisture source in unit air colum and the second is evaporation from unit surface. Discarding evaporation from the underlying surface and transport of water substance in the air, integrated apparent moisture sink must be equal to rainfall; this quantity is expressed as calculated rainfall amount, \(R_{cal} = -\int_{P_{top}}^{P_{SFC}} Q_2 \, \frac{d\rho}{g}\) in this paper. Spatial distribution of \(R_{cal}\) at 12GMT 13 is presented in Fig. 9. Spatial distribution of \(R_{cal}\) agrees well with pattern of \(p\)-velocity. The area of calculated rainfall spreads over the cloud cluster and to the southeast of it. The maximum value of \(R_{cal}\) is \(\sim 5\text{mm/h}\). In the area to the south of the cloud cluster rainfall was not observed (see Fig. 11 of Part I). Therefore the moisture sink there implies an increase of the storage of liquid water content in that region or outward transport of the liquid water. Conversely the moisture source in the area of downward motion spreading to the west of the cloud cluster implies evaporation from liquid water which was transported from the area where condensation took place. However, it is not conclusive, because the influence of neglected terms and so on, is contained within the budget calculation.

The areal-averaged value of the calculated rainfall \(\bar{R}_{cal}\) over the domain consisting of subdomains in and around the cloud cluster is obtained as 

\[
\bar{R}_{cal} = \Sigma S_i \cdot R_{cal,i} / \Sigma S_i
\]

where \(R_{cal,i}\) and \(S_i\) are calculated rainfall and area of these subdomains. The values of \(\bar{R}_{cal}\) obtained at a 12-hour interval are listed together with areas of the domains \(\Sigma S_i\) in Table 3. \(\bar{R}_{ob}\) shown in Table 4 is areal average of the observed 6-hour rainfalls. Positive \(\bar{R}_{cal}\) indicates that there was moisture sink throughout the whole life of the cloud cluster. The maximum value reaches \(\sim 7\text{mm/h}\) at 00GMT 14.

In Part I of this paper, we have analyzed the variation of convective activity within the cloud cluster with about one day period, basing on \(T_{RB}\) data. The values of \(\bar{R}_{cal}\) are \(\sim 3\text{mm/h}\) at 00GMT 13 and \(\sim 7\text{mm/h}\) at 00GMT 14, while they are \(\sim 1\text{mm/h}\) at 12GMT 12 and 12GMT 13. The time variation of \(\bar{R}_{cal}\) also indicates the variation in convective activity with about one day period.

### Table 3 Calculated rainfall.

<table>
<thead>
<tr>
<th>Date</th>
<th>(\bar{R}_{cal})</th>
<th>Dimension</th>
<th>(Subdomains)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12GMT 12</td>
<td>1.18 mm/h</td>
<td>(8.84 \times 10^4) km²</td>
<td>(A)</td>
</tr>
<tr>
<td>00GMT 13</td>
<td>2.70</td>
<td>15.09</td>
<td>(D, E)</td>
</tr>
<tr>
<td>12GMT 13</td>
<td>1.32</td>
<td>19.39</td>
<td>(G, H, I, K, W, X)</td>
</tr>
<tr>
<td>00GMT 14</td>
<td>6.67</td>
<td>14.45</td>
<td>(L, M, Y)</td>
</tr>
</tbody>
</table>

### Table 4 Areal-averaged observed rainfall (\(\bar{R}_{ob}\)) associated with the cloud cluster.

<table>
<thead>
<tr>
<th>Period</th>
<th>(\bar{R}_{ob})</th>
</tr>
</thead>
<tbody>
<tr>
<td>06~12GMT, 12</td>
<td>0.58 mm/h</td>
</tr>
<tr>
<td>12~18GMT, 12</td>
<td>trace</td>
</tr>
<tr>
<td>18~24GMT, 12</td>
<td>0.48</td>
</tr>
<tr>
<td>00~06GMT, 13</td>
<td>0.50</td>
</tr>
<tr>
<td>06~12GMT, 13</td>
<td>0.67</td>
</tr>
<tr>
<td>12~18GMT, 13</td>
<td>1.23</td>
</tr>
<tr>
<td>18~24GMT, 13</td>
<td>3.82</td>
</tr>
<tr>
<td>00~06GMT, 14</td>
<td>2.47</td>
</tr>
</tbody>
</table>
7. Summary and conclusion

A long-lived medium-scale cloud cluster developed in East Asia in the Baiu season has already investigated in Part I of this paper. In Part II, thermal and kinematic properties and heat budget of the cloud cluster have been studied.

As for the cloud cluster located over the Continental China region, the following features were revealed:

1) The environmental air of the cluster has high $\Theta$, $\Theta_e$, and $\Theta^*_e$ in the lower layer (SFC-800 mb), large potential instability $((\Delta \Theta_e/\Delta \rho)_{850-500}=\sim 3K/100 mb)$ and low relative humidity.

2) Thermodynamic quantities of the cloud cluster showed local variations due to medium-scale advection process and due to convective activity of the cluster. The lower troposphere in the cluster is characterized by large instability $((\Theta_{850}-\Theta^*_e_{500})/\Delta \rho=\sim 2K/100 mb)$, and very high relative humidity, though $\Theta$ and $\Theta^*_e$ are nearly equal to those in environment. This is due to the moisture advection in the layer within the cloud cluster.

3) Wind fields in and around the cluster also have localized features. Enhancement of low-level wind in the south side (inflow side) of the cluster, flow with cyclonic curvature at middle levels and enhancement of upper-level wind in the north~northeast side of the cluster are observed.

4) Kinematic properties of the cluster are a medium-scale cyclonic circulation in the lower troposphere just behind (west side) the cluster, an anticyclonic circulation in the upper layer over the cloud cluster and medium-scale upward motion in the cloud cluster. These quantities showed time variations throughout the whole life.

5) When the middle-level cyclonic circulation associated with the cluster was most intense, a medium-scale cold low was found just behind the cloud cluster in the whole depth of the troposphere.

6) Results of heat budget calculations show that an apparent heat source exists in the upper troposphere in the cluster and an apparent moisture sink in the lower troposphere. These also showed significantly large time variation. They reached the maxima at the end of the developing stage of the cloud cluster, when observed rainfall of the cluster attained the maximum.

7) Calculated rainfall (vertically integrated value of the moisture sink) indicates a variation with about one day period. This is consistent with the night-to-morning enhancement of convective activity in the cloud cluster, pointed out in Part I of this paper.

In a word, the thermal and kinematic fields in and around the present cloud cluster over the Continental China region are similar to those of medium-scale cloud clusters developed in the Baiu front over the Japan Islands, though environmental situations were not the same.

In this paper (Part I and Part II), it has been studied the structure and behavior of a Baiu front and an associated medium-scale cloud cluster over the Continental China region. The comparison of them with those over the Japan Islands was also made. By this study, the synthetic features of the Baiu front over the Continent and over the Japan Islands have been described.

It is also an interesting problem to compare the Baiu frontal cloud cluster with “MCC” of U.S.A. However, the detailed analysis on the “MCC” has not been reported yet, therefore the comparative study is a remaining problem.

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References


梅雨前線上の中間規模雲 cluster

第 II 部 熱・運動場と熱収支

秋 山 孝 子

気象研究所

Part I で、中間規模（〜1000 km）雲 cluster の発達過程と微細構造を解析した。Part II では、同 cluster の熱的構造、運動場、および水・熱収支について調べた。解析は、主に cluster が大陸上に位置していた期間 (Part I の formation, developing stages) について行った。以下に結果を要約する。

1. cluster は、大気上の水平に一致でかつ不安定な大気中で発達した。周囲の大気とは対照的で、cluster 近傍の熱水蒸気場は、3 次元移流と対流活発による局所的変動を示している。

2. cluster 近傍の運動場もまた、局所的変動を示している。すなわち、cluster の中～下層に中間規模の低気圧性循環場、上層に高気圧性循環場が形成されており、cluster 内部は上昇流域となっている。それらはいずれも発達過程を通じて認められるが、その絶対値は時間的変動を示す。中層の低気圧循環の極大時、cluster は下層～上層に及ぶ中間規模の cold core を伴っていた。

3. 発達過程を通じて、cluster の下層に apparent moisture sink、中～上層に apparent heat source がある。両者の絶対値は、cluster の降水量極大 (〜80 mm/6 h) に達した時、極大を示す。

4. 計算降水量 (apparent moisture sink の垂直積分値) の時間変動の傾向は、観測降水量のそれとよく一致する。計算降水量は、準日変化を示す。これは Part I で解析された cluster の準日変化を支持するものである。
5. 大陸の一部かつ不安定な大気中で発達したこの cluster の熱的構造・運動場は、傾圧域である日本列島上の中間規模雲 cluster のそれらと、cluster のおかれている環境は異なるけれども、類似的状況を示していた。

長続した中間規模雲 cluster について、以上の解析結果から、以下のことが結論される。cluster は大陸上の傾压性の少ない不安定気層内では、対流活動をとおして潜熱の解放・再配分があったもの、中間規模 cluster にとどまり、depression にまで発達しない。cluster は、傾圧域上の short wave trough の影響下では、frontal depression へと発達する。