The Development of the Medium-scale Disturbance in the Baiu Front*

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Abstract

On July 04, 1969, severe precipitation took place over the Japan Islands with the passage of medium-scale disturbances along the Baiu front. The structure and the process of the development of the disturbance are analysed in detail by using the data of the Severe Rainstorms Research Project and satellite cloud pictures.

The satellite and radar pictures show that the disturbance is accompanied by a well organized medium-scale cluster of convective clouds. Detailed analyses of rawinsonde data inside the disturbance revealed that the deepening of the surface pressure is deeply related to the formation of a mid-tropospheric warm core accompanied by a significant field of convergence in the lower troposphere. The high humidity in the warm core and the intense precipitation suggest that the formation of the warm core is due to the process of so-called convective warming, i.e. the release of latent heat and the upward transport of heat energy caused by cumulus convections. The formation of the convergence field is due to the increase of low-level wind velocity over the intense rainfall area. The active cumulus convections in the sheared westerly transport the momentum downward and therefore work to increase the low-level wind velocity.

1. Introduction

Since the Norwegian school proposed their polar front model in the 1920's (Bjerknes and Solberg 1922), various analyses on the structure and the behavior of the polar front and the associated cyclone have been made by many authors, and the well-known synoptic model of the polar front, cyclone and jet stream was established in the middle of this century (e.g. Palmén and Newton 1969). On the other hand, theoretical studies revealed that the development of the synoptic-scale disturbance in middle latitudes is essentially related to the so-called baroclinic instability of the atmosphere.

It is observationally known, however, that disturbances of smaller scale sometimes develop along the frontal zone. These characteristics seem to be discordant with the character of the synoptic-scale cyclone. Recently some theoretical meteorologists have recognized the necessity of studying these small-scale cyclones as intermediate-scale phenomena in the atmosphere (Eliassen, 1964). Orlanski (1968) re-examined the instability of wave disturbances embedded in the classical Norwegian polar front and found that unstable waves exist in the short-wave regime. In their theoretical studies on the property of baroclinic stability in the atmosphere, Gambo (1970 a and b) and Tokioka (1970) pointed out that the growth-rate maximum exists in the shorter wave length when Richardson number is of the order of unity.

It should be necessary to analyse the structure and behavior of these small-scale disturbances in more detail, because the results of the analyses can verify the validity of the results of theoretical study and also provide necessary information for the numerical experiment.

The rainy season in East Asia, called Baiu in Japan and Mai-yü in China, comes in early summer. Heavy precipitation takes place along the Baiu front, the subtropical stationary front found along the boundary between the tropical-monsoon air-mass and the air-mass in middle latitudes. A family of small cyclones frequently develops along the Baiu

* This work was done based on the observation data obtained by the Experiment of the Severe Rainstorms Research Project.
front and sometimes causes intense rainfalls. In order to clarify the mechanism of heavy rainfalls in the Baiu season, experiments have been carried out by the Severe Rainstorms Research Project of the Japan Meteorological Agency in the Kyushu District and its adjacent oceanic area since 1968.

By analysing the data of the Experiment of 1969, Matsumoto, Ninomiya and Yoshizumi (1971) pointed out that the Baiu front, different from a polar front, has a less concentrated thermal gradient but is accompanied by a low-level jet stream. They found also that medium-scale disturbance with a wave length of 500–1000 km prevails in the frontal zone. Kinetic energy is concentrated in the lower troposphere just north of the low-level jet axis where Richardson number is nearly unity.

In the analyses of time-lapse composite echo map, Matsumoto and Tsuneoka (1970) showed that the medium-scale disturbance is accompanied by an organized echo cluster.

During the one week period of the second Experiment in 1969, a large amount of rain fell over the Japan Islands in association with the passage of successive medium-scale disturbances along the Baiu front (Matsumoto, Ninomiya and Yoshizumi 1971). The medium-scale disturbance of July 04, 1969, was generated over the sea adjacent Kyushu and developed during its passage along the Japan Islands. Therefore, the process of its formation and development was observed in detail by the observation network covering the Japan Islands.

In the present paper, the structure and development of the disturbance will be analysed in detail by using the data of the Experiment and also satellite cloud pictures. The analyses will be made with special emphasis on the role of cumulus convection in the process of the development of the medium-scale disturbance.

Disturbances smaller than synoptic-scale but larger than cumulus-scale are called generally intermediate-scale disturbances. It is observationally recognized that there are two kinds of intermediate-scale disturbances in Baiu season, i.e. the medium-scale disturbance with a wave-length of 500–1000 km and the mesoscale one of about 100 km (Matsumoto and Akiyama 1970).

2. Synoptic situation of the Baiu front

Let us begin with a brief explanation of the observation network used in the present analyses. The network of aerological, radar, marine and surface stations in and around the area of the Experiment is presented in Fig. 1. Five observation ships, four in the area of the Experiment and one in the Pacific off the coast of the Japan Islands, participated in the Experiment. Aerological observations were made every 6 hours at ten aerological stations including four fixed ship stations. The circles entered in Fig. 1 show the range marks of radar network. Since the disturbance of July 04 developed while passing along the Japan Islands where sufficient data are provided by the dense observation network, we are able to analyse the process of formation and development of the disturbance in detail.

Now we will describe the synoptic weather situation of July 04, 1969. In the beginning of July 1969, the Baiu front with continual heavy rainfall lay almost stationary over the Japan Islands. Especially intense rainfall took place in July 04. The distribution of the total amount of rainfall during the 24 hours from 0900 LST July 04 to 0900 LST July 05 is presented in Fig. 2. The zone of strong precipitation is found along the Pacific coastal region of the Japan Islands, where the maximum amount of precipitation exceeded 300 mm.

Shown in Fig. 3 is the 500-mb map at 2100 LST July 04, 1969, where the geopotential height contours, isotherms and the moist area in which the dewpoint depression is less than 2°C are indicated by solid lines, broken lines and the hatched area respectively. A beltlike zone of warm and moist air flow, the so-called moist tongue extended eastward from the lower Yangtze region of the Chinese Continent to the Japan Islands. In addition, the axis of the strong wind was found in the moist tongue. The features mentioned above are considered the characteristics of the Baiu front associated with heavy rainfall (see Matsumoto, Ninomiya and Yoshizumi 1971). A weak cut-off cold cyclone at 500 mb accompanied by a moderately developed synoptic-scale cyclone was located over the Korea Peninsula.

From the conventional synoptic model of cyclone, it may be supposed that this heavy rainfall was caused by the passage of a
Fig. 1. Observation network used in the analysis.

Fig. 2. Distribution of the rainfall amount during the 24-hour period from 0900 LST July 04 to 0900 LST July 05, 1969.

Fig. 3. The 500-mb map at 2100 LST, July 04, 1969. The moist area in which dewpoint depression is less than 2°C is indicated by hatches.

3. medium-scale aspects of cloud distribution in the Baiu front revealed by satellite cloud pictures and composite radar echo maps

We will study the medium-scale aspects of cloud distribution in the Baiu front by inspecting the satellite cloud pictures. Shown in Fig. 4 and Fig. 5 are the cloud pictures taken from ESSA-9 at 1444 LST, July 04, 1969,
As is seen in the figures, a large-scale cloud zone is found along the Baiu front and/or the moist tongue. Inspecting them in detail we will notice, however, that the cloud distribution is not necessarily uniform along the Baiu front but the clouds are organized into a medium-scale cluster whose diameter is a few hundred km. At 1444 LST, July 04 (see Fig. 4), there is a cloud cluster accompanied by a synoptic-scale cyclone over the eastern East China Sea adjacent to the Kyushu District. Besides, there is another well organized cloud cluster over the middle Japan Islands. The mesoscale cloud bands extend southwestward from the cluster. As seen in the surface weather map at 1500 LST July 04 in Fig. 4, the cyclonic circulation of the surface wind is found under the cloud cluster (marked by “A” in the figure). However, we can not recognize a low pressure area of the disturbance as a closed isobar at this time. Similar cloud clusters are found over the western East China Sea and the Chinese Continent.

Next, we inspect the cloud picture at 1347 LST, July 05 (Fig. 5). Again, we recognize a row of medium-scale cloud clusters in the Baiu frontal zone. In other words, the large-scale cloud zone consists of a row of medium-scale cloud clusters. Especially well organized, vortex-shaped clusters are found in areas marked by “A” and “B” in the figure. As will be clear from the discussions below in sections 4 and 5, the result of the analyses using radar and surface observation data shows that the cloud cluster “A” in Fig. 4 (i.e. 1444 LST, July 04) developed into the medium-scale cyclone “A” in Fig. 5 (i.e. 1347 LST, July 05).

* Usually, a well-developed large-scale cloud vortex is found over the occluded cyclone accompanied by the predominant cut-off cold vortex aloft (Boucher and Newcomb (1962), Widger (1964)). It should be noticed that the vortex-shaped cluster under consideration is different from the large-scale cloud vortex mentioned above.
LST, July 05) during the passage along the Baiu front.

The features of the medium-scale disturbance revealed by satellite cloud pictures should be reexamined by using the radar echo pictures. Shown in Fig. 6 is the composite echo map with the surface weather map at 1500 LST, July 04, 1969. The cloud cluster “A” in Fig. 4 is clearly recognized as a medium-scale echo cluster in the composite echo map. As mentioned above, we find a cyclonic circulation of the surface wind under the echo cluster. The dense echoes concentrated in the eastside of the center of the cyclonic circulation and the echofree area is found in the rear of the center. This echofree area appears as a cloudless area in the satellite pictures.

As conclusion to this section, we should notice that the medium-scale disturbance in the Baiu front is closely related with the organized cluster of convective clouds and that it develops in the region far from the synoptic-scale cyclone accompanied by the cold trough aloft.

4. The development process of the medium-scale disturbance revealed by surface observation data

The development process of the medium-scale disturbance will now be analyzed in detail by using surface observation data.

The diagrams shown in Fig. 7 are the hourly rainfall records from 0000 LST July 04 to 1800 LST July 05 at surface stations located at intervals of about 100 km along the path of the disturbance. It is clearly seen in Fig. 7 that the maximum rainfall intensity propagated steadily eastward. Inspecting the satellite cloud picture (Fig. 4) and radar echo map (Fig. 6), we know that the cloud cluster “A” passed over the Kii Peninsula (i.e. Shionomisaki 778) at 1500 LST. Therefore we can conclude that the maximum rainfall intensity is associated with the medium-scale disturbance “A”. It is an interesting fact that there are two or three peaks of precipitation in the medium-scale disturbance “A”. They pointed out that the variation of rainfall intensity with a period of 2-3 hours was caused by the mesoscale disturbances with heavy rainfall. The behavior of the mesoscale disturbances with heavy rainfall was analyzed in detail by Matsumoto and Akiyama (1969 and 1970). They pointed out that the variation of rainfall intensity with a period of 2-3 hours was caused by the mesoscale disturbances. The short period variation that appears in Fig. 7, therefore, suggests that a few mesoscale disturbances are embedded in the medium-scale disturbance “A”.

We will now examine the surface pressure
field. As already mentioned in section 3, the amplitude of pressure in a medium-scale disturbance, especially in the initial stage of its development, is very small, and therefore it is difficult to analyze it in conventional surface weather maps. It is more adequate to analyze the field of pressure tendency, $\partial p/\partial t$, rather than to analyze the pressure field itself. Of course, the observed value of $\partial p/\partial t$ includes the pressure tendency due to the diurnal pressure variation and also the synoptic-scale disturbances. Since we are concerned with the pressure tendency of the medium-scale disturbance only, it would be better to eliminate the effect of the diurnal variation and synoptic-scale disturbances. For this purpose, we calculated $\partial p/\partial t$, the areal-averaged value of $\partial p/\partial t$ over the west and central regions of the Japan Islands, and then we subtract $\partial p/\partial t$ from the observed value of $\partial p/\partial t$. The value of $\partial p/\partial t - \partial p/\partial t$ is considered therefore, to represent the pressure tendency due to the medium-scale disturbance only.

The diagram shown in Fig. 8 is the time-section of $(\partial p/\partial t - \partial p/\partial t)$. In the time-section, time and horizontal distance along the path of the disturbance are scaled along the ordinate and abscissa respectively. The negative value of $(\partial p/\partial t - \partial p/\partial t)$, i.e. the pressure-fall and the positive value, i.e. the pressure-rise are indicated by hatches and stiples. The most notable pressure falls appearing in the time-section are marked by “A” and “B”, which correspond to the cloud clusters “A” and “B” in Figs. 4, 5 and 6. In the present study, we are mainly concerned with the disturbance “A”. The path and the successive position of the disturbance “A” is given by a thick line and black circles in the map attached in the time section.

We have seen the cyclonic circulation of the surface wind within the medium-scale cloud cluster “A” in section 3. Let us now analyze the surface wind field by calculating the vorticity and divergence of surface wind over small triangular areas enclosed by three surface stations. The results of calculation

![Fig. 8. Time section of the surface pressure tendency.](image_url)

![Fig. 9A. Time change of the surface wind vorticity.](image_url)
are given in Fig. 9A (vorticity) and Fig. 9B (divergence). The numerals in the left side of the figure are the station number used for the calculation. As evident from Fig. 9A, we can recognize the passage of the disturbance as the maximum of cyclonic vorticity from the initial stage of the development, while the maximum of convergence is not found in the initial stage.

We will reexamine the results of the time section analyses by looking at the 3-hourly maps of the surface wind and the pressure tendency \( \frac{\partial p}{\partial t} - \frac{\partial \vec{v}}{\partial t} \) (Fig. 10).

The development of the disturbance is very slow in the formation stage or initial stage of development, i.e. from 0300 LST to 1500 LST, and the cyclonic vorticity and the convergence are intensified gradually after 1500 LST simultaneously with the deepening of the surface pressure.

5. The structure and the developing process of the medium-scale disturbance analyzed by composite radar-echo maps

Let us describe the development process of the medium-scale disturbance "A" by analyzing composite radar-echo maps. Shown in Fig. 11 are the 3-hourly composite echo maps during one day period from the formation stage to the stage of the maximum development. These maps are obtained by using the echo pictures at seven radar stations, i.e. the ship Ryofu-maru, Mt. Sebur, Tanegashima, Hiroshima, Muroto, Nagoya and Mt. Fuji. The position of the maximum pressure fall determined by the surface analyses in section 4 is indicated by a cross in the maps.

Although a few mesoscale echo clusters exist in the vicinity of the disturbance in the formation stage (0600 LST), they are not considered yet as an organized medium-scale echo cluster. The echo was weakened once when they passed over the lee side of a mountain range in Kyushu (see map at 0900 LST).
While passing over the Pacific coast area of Shikoku, however, the echo group was re-intensified remarkably, developing rather rapidly into a well organized medium-scale echo cluster as seen on the map for 1500 LST. We mentioned already from the analysis on surface observations that the disturbance was intensified remarkably after 1500 LST (section 4). This suggests that the development of the disturbance is closely related with the cumulus cloud activity within the disturbance.

From the echo maps in the developing stage after 1500 LST, we can point out some characteristic features of the echo cluster associated with the medium-scale disturbance. The most dense echoes, i.e. the most active cumulus convections, are concentrated east and/or southeast of the center of the disturbance. We notice a few mesoscale echo bands extending southwestwards from the region of the dense echo (see maps at 1500 LST, July 04 and at 0425 LST, July 05). This mesoscale band structure of echo is also recognized on the satellite cloud picture (Fig. 4) as well-developed cloud bands. This kind of band structure of convective clouds is frequently observed in the Baiu season (Matsumoto and Ninomiya 1971) and seems to be one of the characteristics of the convective cloud in the Baiu front.

The rear-left part of the disturbance is, on the other hand, characterized by an echo-free area, which is recognized as a clear area on the satellite cloud picture (see Fig. 4 and Fig. 5).

The character of echo distribution will be reexamined by using the precipitation data. The upper figure in Fig. 12 indicates the path of the disturbance and the network of rain-gauge stations over the western Japan Islands. The positions of stations are rearranged relative to the center of the disturbance as shown in the lower figure of Fig. 12. Then the area under consideration is divided into 16 subareas bounded by concentric circles at 100-km intervals and radii at 45 degree intervals. Then we calculate the areal mean amount of rainfall in each subarea. The distribution of rainfall within the disturbance thus obtained coincides well with the distribution of the movement of medium-scale disturbance and precipitation stations.
radar echo. The maximum amount of rainfall is observed east and/or southeast of the center and the minimum in the rear left.

This asymmetric distribution of echo and rainfall suggests an asymmetric convergence field in the lower layer. In order to verify the supposition, we will again examine the surface wind field. First, the normal and tangential components of the surface wind are calculated by using the cylindrical coordinate centered on the disturbance. Then, by a similar procedure to that used in precipitation analysis, we get the mean composite wind field as shown in Fig. 13. As a matter of fact, a cyclonic circulation is observed in Fig. 13. It is interesting to notice the asymmetry of the wind field. In the northeast quadrant an easterly wind is predominant, while a strong southeasterly predominates in the southeastern quadrant. There are strong convergence fields east of the center of disturbance where cumulus activity is most intense.

6. The structure of the medium-scale disturbance in the initial stage

In this section, the three-dimensional structure of the medium-scale disturbance will be described by using aerological data. We already mentioned in sections 4 and 5 that the features of the development before 1500 LST are different from those after 1500 LST. The period from 0300 LST to 1500 LST, July 04 and that from 1500 LST July 04 to 0600 LST July 05 may be called as the initial and the developing stage respectively.

The structure of the disturbance in the initial stage will be analyzed by means of vertical time section. Since diurnal variations of temperature and geopotential height (see Kurihara 1962, Harris, Finger and Teweles 1962) are not negligible as compared with variations due to the medium-scale disturbance, it is necessary to eliminate diurnal variations from the observed values.

Here we use aerological data observed at 8 stations over the western Japan. Observations were made every 6 hours (i.e. at 0900, 1500, and 2100 LST) during the 7-day period. The temperature is expressed as $T_t, d, t(P)$ where subscripts $i(1-8)$, $d(1-7)$ and $t(1-4)$ stand for station, day and time of observation respectively. The averaged value for the 7-day period of the temperature at a certain observation time $t$ is given as $[T_t, t(P)] = \frac{1}{7} \sum_i T_{t, i, t(P)}$ and the averaged value for the period is given as $[T_t(P)] = \frac{1}{7} \sum_i T_{t(P)}$. Consequently, the deviation of $[T_t, t(P)]$ from $[T_t(P)]$, i.e. $\Delta T_t, t(P) = [T_t, t(P)] - [T_t(P)]$ will give the diurnal variation of temperature at each station. By comparing the values of $\Delta T_t, t(P)$ at 8 stations, however, we notice some irregularity among them. In order to avoid this, we calculate the areal mean of $\Delta T_t, t(P)$ over western Japan as $\Delta T_t(P) = \frac{1}{8} \sum_i \Delta T_{t, i}(P)$. The values $\Delta T_t(P)$, i.e. the mean diurnal variation of temperature thus obtained, are given in Table 1. An amplitude of about 0.8°C is found in the upper troposphere.

By using the same procedure, the diurnal variation of geopotential height $\Delta \phi_t(P)$ is calculated and shown in Table 2. The amplitude in the upper troposphere is as much as 25 g.p.m.

Shown in Fig. 14 is the vertical time section of the anomaly temperature field, defined as $T_{t, d, t}(P) = T_{t, d, t}(P) - ([T_t(P)] + \Delta T_t(P))$, at Shionomisaki (station number 778). Also the vertical time section of wind velocity and relative humidity is shown in the lower part of
Table 1. The diurnal variation of temperature, $dT_T(p)$, (unit °C)

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<th>15</th>
<th>21</th>
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Table 2. The diurnal variation of geopotential height, $d\phi(p)$, (unit g.p.m.)

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<td>-16</td>
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</table>

Fig. 14. We know that the medium-scale disturbances “A” and “B” passed over Shionomisaki at 1500 LST July 04 and 0300 LST July 05 respectively (sections 4 and 5). The interesting fact observed within the disturbances is the existence of a thick moist layer penetrating into the upper troposphere and a remarkably warm air in the middle and the upper troposphere. We will discuss this warming in section 7 in more detail.

Another important feature within the disturbance in the initial stage is the existence of relatively cool air in the lower troposphere between 900 and 700 mb. The high humidity indicates a strong upward motion within the disturbance. The fact that this air is cool, therefore, suggests indirect circulation in the lower layer. In their analyses of the kinetic energy balance in the Baiu frontal zone for July 1968, Matsumoto, Yoshizumi and Takeuchi (1970) also pointed out indirect circulation. From the fact that the medium-scale disturbance developed in spite of indirect circulation, they concluded that the kinetic energy of the intermediate-scale disturbance is transformed from that of convective-scale motions.

We notice in the lower figure in Fig. 14, that the wind velocity in the lower layer within the disturbance increases remarkably. The almost uniform wind speed in the thick convective layer suggests that the convective downward transport of the momentum causes an increase of the low-level wind speed.
At the end of this section the vertical tilt of the trough line of the disturbance will be discussed. It is hard to solve this problem by analyzing the value of geopotential height itself. Therefore, we treat the value of anomaly geopotential height
\[ \phi'_{t, s, t}(P) = \phi_{t, s, t}(P) - \left( \phi_t(P) + \delta \phi_t(P) \right) \]
where \( \phi_t(P) \) is the 3-term running mean value is calculated and presented in Fig. 15. As naturally expected from the thermal field, the trough line tilts eastward due to the cold air in the lower troposphere. On the other hand, there appears a ridge line in the upper troposphere over the low-pressure center at the surface, because of a thick layer of warm air.

7. Convective warming over the medium-scale disturbance

In the previous section we found the middle and upper tropospheric warming over the medium-scale disturbance by analyzing the vertical time section of the air-temperature. We will now analyze the warming on the 300-mb maps. Shown in Fig. 16 are the thermal and the wind field on the 300-mb surface at 0300, 0900, 1500 and 2100 LST.
sensible heat and moisture, and also release the latent heat and therefore cause the warming. We may call the process convective warming. Similar warming accompanied by a convective disturbance was also reported by several authors (e.g. Fujita and Byers (1960), Matsumoto and Ninomiya (1967) and Ninomiya (1971A)). The formation of a warm core in the tropical cyclone (Yanai 1968) may be mentioned here as an analogous situation, though there is some difference between a tropical cyclone and a mid-latitude medium-scale disturbance.

We will next discuss the influence of convective-warming on the upper wind field. There is a considerably strong thermal gradient in the upper troposphere to the north of the moist tongue along the Baiu front (see also Matsumoto, Ninomiya and Yoshizumi 1971). The formation of a warm area over the Baiu front results in an increase in the thermal gradient to the north of the warm area. The thermal gradient thus intensified causes an increase in the vertical wind shear towards the balance required from the thermal-wind relation, although the medium-scale wind field is not completely geostrophic. Shown in Fig. 17 is the 300-mb thermal field and the observed wind shear in the layer between the 200 and 300-mb surface at 0900 LST July 04. An area of convective warming is located over the Shikoku District while an area of strong wind-shear (50 knot/100 mb) is found along the northern and northeastern border of the warm area.

The successive positions of the area of convective warming and that of the maximum wind-shear are entered in Fig. 17. It is at once noticed that the latter moved east-northeastwards accompanied by the warm core. It is interesting to notice that the medium-scale disturbance caused medium-scale intensification of the upper-level jet stream through the process of convective warming. Similar but more intense intensification of the jet stream north of a thunderstorm cluster was reported by Ninomiya (1971B).

Before concluding the present section, let us make a brief reference to the convergence of the water-vapor flux within the disturbance. Shown in Fig. 18 is the vertical distribution of the convergence of water-vapor flux calculated over the quadrangle enclosed by the aerological stations Wajima, Tateno, Hachijojima and Shionomisaki at 2100 LST July 04.

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![Fig. 17](image1.png)

Fig. 17. The 300-mb thermal field and observed wind shear in the layer between the 200 and 300-mb surface at 0900 LST, July 04, 1969. The movement of the area of convective warming and the area of maximum wind shear are also entered in the figure.

![Fig. 18](image2.png)

Fig. 18. Vertical distribution of the convergence of water-vapor flux calculated over the area enclosed by aerological stations Wajima, Hachijojima, Shionomisaki and Wajima at 2100 LST, July 04, 1969.
closely resembles that obtained by Matsumoto (1968) over the heavy rainfall area of July 09, 1967. A strong convergence of water-vapor flux is found in the lower troposphere under the 700-mb surface, while there is a considerably strong divergence in the middle troposphere. The vertical integration of moisture convergence gives the amount of condensed water in the free atmosphere if we neglect the local time change and evaporation (they were actually negligible in this case). The value of condensed water thus estimated is about 50 mm/day (c.f. the rainfall amount shown in Fig. 2). It should be noticed that the cluster of the convective cloud is maintained by the moisture convergence in the lower layer.

8. Change of the structure of the medium-scale disturbance.

In the present section we will analyze the changes in the circulation and thermal structure of the medium-scale disturbance and relate the changes to the development of the disturbance.

First, we will reexamine the situation in the initial stage by looking at the 850 and 700-mb maps at 0300 LST, July 04 (Fig. 19).

As was already pointed out in the vertical-time section analyses (Fig. 14), there is a relatively cool area over the center of the medium-scale disturbance at 850 and 700-mb. The cool area at 700-mb is characterized by high humidity. On the other hand, the remarkably warm region at 700-mb in the rear-left of the disturbance is characterized by dryness. A similar dry and warm area appears frequently in the rear-left of a heavy rainfall area (Matsumoto and Ninomiya (1971), Ninomiya (1971 B)). It seems to be due to the adiabatic descending motion in the rear-left of the disturbance. Although the cyclonic circulation is not yet formed at 850-mb, a strong wind is caused within the disturbance and therefore a strong convergence field is generated in front of it.

We will now describe the situation in the development stage by analyzing the 700 and 400-mb maps at 2100 LST, July 04 (Fig. 20). In the developing stage, convective warming prevails in the whole troposphere. A remarkable warm core has been formed within the disturbance at 700-mb as well as 400-mb surface. We may conclude that the medium-scale disturbance did not develop remarkably until the convective warming has been completed in the lower layer. Or in other words, it begins to develop rather rapidly when or after the direct circulation has been completed. It goes without saying that the convective warming at this stage is most remarkable at the 400 and 300-mb surface.

One of the interesting features found at 400-mb is the moist outflow over the disturbance. The moisture is transported into the upper troposphere through the warm core by convective motion, and then transported forwards in the form of moist outflow as seen in the 400-mb map in Fig. 20. This situation resembles the situation of moist outflow found over the heavy rainfall area (Matsumoto (1968)) and in severe storms (Ninomiya (1971 B)).

As the last topic of this section, the wind field in the developing stage of the disturb-
ance will be described. At 2100 LST, a cyclonic circulation is found not only in the lower layer but also at the 700 and 600-mb surface. The effect of the convective mixing of horizontal momentum is now prevailing in the thick layer. The increasing low-level wind and decreasing upper-level wind within the disturbance caused the low-level convergence and upper-level divergence in front of the disturbance respectively. Their magnitude is as large as $5 \times 10^{-8}$ sec$^{-1}$. The intensified low-level convergence and upper divergence thus intensified work to maintain the continuous development of cumulus convections and propagate the disturbance. It is concluded that this process caused by convective mixing plays an important role in the development of the medium-scale disturbance in both the initial (see section 6) and the developing stage.

9. Concluding remarks

A medium-scale disturbance with a wave length of 1000–500 km travels along the Baiu front, and causes a periodic maximum of rainfall with a period of 10–20 hours.

In the present paper, detailed synoptic analysis is made on the behavior and structure of the medium-scale disturbance which developed over the Japan Islands on July 04, 1969. It developed about 700 km to the east of a synoptic-scale cyclone accompanied by an upper westerly trough. According to the features of the disturbance, we will call the 10-hour period after its generation the initial stage and the period later the development stage.

In the initial stage, the disturbance appears on radar echo pictures or satellite cloud pictures as an unorganized echo or cloud cluster with intense rainfall. Although no cyclonic wind field can be found in the stage, there is a low-level strong wind within the cluster and the convergence in front of it. The influence of convective warming begins to appear in the middle and upper troposphere. On the other hand, there is a relatively cool area in the lower layer and, therefore, an indirect circulation within the cluster. The fact that it develops slowly in spite of the indirect circulation, suggests the important role played by the convective mixing of momentum in the developing mechanism in the initial stage.

During the initial stage, the disturbance develops gradually, i.e. the surface pressure deepens and a cyclonic circulation is formed gradually. The echo cluster developed into a well-organized vortex-shaped cluster in the developing stage. The convective warming prevail in the whole troposphere and the direct circulation has been completed in the lower troposphere. Then the disturbance begins to develop rather rapidly.

The increasing low-level wind and decreasing upper-level wind within echo cluster suggest the work of convective momentum mixing. The strong low-level convergence in front of the strong wind area produces a favorable condition for the continuous development of convective motions and maintaining the echo cluster. During the 25–30-hour period after the formation, the medium-scale cloud cluster develops into a medium-scale cyclone in the Baiu front.

From the result of analysis it will be concluded that the interaction between cumulus convection and the medium-scale disturbance plays an important role in the development of the medium-scale disturbance.

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