Large, Synoptic and Meso Scale Variations
of the Baiu Front, during July 1982

Part II: Frontal Structure and Disturbances

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Abstract

In part I of this study, cloud variations in/around the Baiu front in July 1982 were studied. The purpose of Part II is to clarify inclusively the structure of the Baiu frontal zone and features of the Baiu frontal disturbances which would be related to the cloud variations studied in Part I, analyzing relative vorticity fields in July 1982. Attention is focused on the relationship and interaction between the upper westerly jet (W-jet) in 40°N-50°N and the Baiu low-level jet (B-jet) in 30°N-40°N.

In monthly mean, the Baiu frontal cloud zone, which was formed in 30°N-40°N, coincided with a low-level positive vorticity zone associated with a B-jet. Over the continent, the positive vorticity zone was confined to the lower layer. The zone merged with the positive vorticity zone associated with the W-jet around the east coast (120°E) of the continent. Over the region east of 120°E (Japan-northwestern Pacific), the deep positive vorticity zone of a baroclinic structure was formed in the Baiu frontal zone. This will account for the difference in cloud features of the Baiu frontal mesoscale systems between the continent and the Japan-northwestern Pacific region described in Part I.

With the change of large-scale circulation in East Asia, the relationship between the W-jet and the B-jet changed during the analysis period. Concurrently, the frontal structure, features of disturbances and cloud amounts in the Baiu front, also changed significantly in the 120°E-140°E region. Three situations of the Baiu front ((1) active-deep, (2) active-shallow and (3) inactive phases) are classified. The vertical structure of the Baiu front and features of the disturbances in these three phases are studied in detail. Over 120°E-140°E, the Baiu frontal mesoscale disturbances showed a deep-baroclinic structure in the active-deep phase, while in the active-shallow phases they showed a shallow structure and located to south of the deep mesoscale disturbances in the northern frontal zone of the W-jet. In both active phases, the mesoscale disturbances in the Baiu frontal zone began to develop around the east coast (120°E) of the continent under the influence of the upper-level disturbances in the W-jet propagated from Central Asia.

1. Introduction

The Baiu front is a sub-tropical stationary front formed over East Asia (the 30°N-40°N latitude zone from the northwest Pacific to the China Continent through Japan) during the summer monsoon. The Baiu front is a long precipitating zone. In the zone, various scales of precipitating systems develop.

Recently some papers clarified large-scale features of the Baiu front on 5-day or 10-day mean fields (e.g., see Akiyama, 1973; Kato, 1985; Ninomiya and Muraki, 1986). In these studies, however, neither the structure of the whole Baiu frontal zone from the China Continent to the northwest Pacific, nor the difference in the structure between active and inactive phases of the Baiu front, has been fully discussed.

Some case studies revealed that the Baiu frontal rainfalls were caused by medium-scale (~1000 km) organized cloud systems associated with frontal depressions or synoptic-scale lows (e.g., Matsumoto et al., 1970; Ninomiya and Akiyama, 1971, 1974; Yoshizumi, 1977; Akiyama, 1978). These case studies clarified day-to-day variations of the Baiu front. However, these studies have dealt with the Baiu front only over the Japan Islands.

It has been pointed out that many vortices were generated over the Qinghai-Xizang Plateau during the summer monsoon, and some of them moved eastward and brought rainfalls over central China (e.g., see Tao and Ding, 1981; Kuo et al., 1984). Murakami and Huang (1984) have studied, by composite analysis, the structure of mesoscale (about 1000
km) vortices which generated around the Quinghai-Xizang Plateau and caused heavy rainfalls over central China in the Baiu season. In these studies, however, the relationship between the vortices and the Baiu frontal zone has not been discussed clearly. Ma and Bosart (1987), in a case study on a heavy rainfall event occurring in a quasi-stationary front (the Baiu front) of South China, pointed out that a short-wave trough north of the Plateau and a very weak short-wave trough south of the Plateau played important roles in the event. Ninomiya et al. (1981) and Akiyama (1984 a, b) studied the evolution process of a medium-scale cloud cluster which generated at the eastern foot of the Quinghai-Xizang Plateau and propagated to the east on the Baiu frontal zone and then caused heavy rainfalls over the Japan Islands.

To understand further the Baiu frontal activity, it is necessary not only to examine space and time variations of cloud/rainfall in the frontal zone but also to clarify the behavior of disturbances in and around the whole Baiu frontal zone from the west (over the China Continent) to the east (over the Northwest Pacific).

Akiyama (1989; Part I of this study), analyzed space and time variations of clouds in the Baiu frontal zone in July 1982, by using GMS-IR data. The results of Part I revealed that the variations of clouds in the eastern portion of the Baiu front (over Japan to the northwest Pacific) differed from those in the western portion (over the continent).

The purpose of Part II is to clarify inclusively the structure of the Baiu frontal zone and features of the Baiu frontal disturbances, which would be related to the cloud variations studied in Part I, analyzing relative vorticity fields in July 1982. In Section 2, the data will be described. In Section 3, an overview of the analysis period will be discussed in terms of the monthly mean fields. Section 4 describes the time change of the frontal structure during the analysis period, based on 5-day mean fields. Special attention is given to the relationship between the Baiu front and the upper westerly jet. From the vertical structure of the frontal zone and the amount of high-cloud (Ch) in the frontal zone, three situations (phases) of the Baiu front, i.e., active shallow-type, active deep-type and inactive phases, are classified. Circulations in and around the Baiu front, and characteristics of the frontal disturbances in these three phases will be noted in Sections 5, 6 and 7, respectively. In Section 8, features of the frontal disturbances will be discussed by examining time series data during the analysis period. Section 9 offers concluding remarks.

2. Data, the analysis period and the use of relative vorticity fields

Main upper data used in the present study are 12-hourly grid point values of Fine Mesh Analysis (FANAL) Data at mandatory pressure levels, which were prepared by the operational fine-mesh objective analysis system of the Numerical Prediction Division, JMA. The grid distance of FANAL data is about 254 km at 60°N latitude on the polar stereographic projection map. The analysis domain in this paper is shown in Fig. 1. To describe large-scale characteristics of the Baiu frontal structure and frontal disturbances, the analysis period (July of 1982) is subdivided into six 5-day periods, as shown in Table 1. The time scales defined in Table 2 are used in this study.

To investigate the structure of the Baiu frontal zone and features of Baiu frontal disturbances, the

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Table 1. Subdivision of the analysis period and classification.

<table>
<thead>
<tr>
<th>Subperiod</th>
<th>Frontal activity</th>
<th>Frontal structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period 1</td>
<td>01-05 Jul 1982</td>
<td>(T.D.)</td>
</tr>
<tr>
<td>Period 2</td>
<td>06-10</td>
<td>Inactive</td>
</tr>
<tr>
<td>Period 3</td>
<td>11-15</td>
<td>Active shallow-type</td>
</tr>
<tr>
<td>Period 4</td>
<td>16-20</td>
<td>Active shallow-type</td>
</tr>
<tr>
<td>Period 5</td>
<td>21-25</td>
<td>Active deep-type</td>
</tr>
<tr>
<td>Period 6</td>
<td>26-30</td>
<td>Inactive</td>
</tr>
</tbody>
</table>

Table 2. Explanation of the time-scales used in this paper.

<table>
<thead>
<tr>
<th>Time-scale</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large-scale</td>
<td>Longer than ~6 days</td>
</tr>
<tr>
<td>Synoptic-scale</td>
<td>~6-day period</td>
</tr>
<tr>
<td>Mesoscale</td>
<td>One to 2~3-day period</td>
</tr>
</tbody>
</table>
Fig. 2. 31-day (1~31 July, 1982) mean temperature at 300 mb, 500 mb, 700 mb and 850 mb. The isoline interval is 1°C. The black areas at 850 mb and 700 mb represent mountains higher than 1500 m and 3000 m, respectively. The thick broken lines represent the positions of maximum Ch amounts (the Baiu front).

analysis will be made mainly of relative vorticity fields. Relative vorticity ($\zeta$, abbreviated as “vorticity” hereafter) is calculated from the wind data of FANAL. The mesoscale disturbances developed in the Baiu front have small amplitude in height fields, as seen in Fig. 15. The analysis of relative vorticity fields are useful for picking up small-scale circulation systems, because $\zeta$ is a differential property of wind field and, for quasi-geostrophic systems, a second differential property of height field.

3. Overview of the analysis period

Characteristics of the Baiu front in one month (1~31 July, 1982) mean fields will be described. Figure 1 shows the distribution of mean high-cloud (Ch, see Part I of this study) amounts. A zone of Ch amounts greater than 30% extends from 150°E/35°N to 90°E/30°N. This zone of the maximum Ch amounts corresponds to the Baiu frontal zone. The Ch amounts over the continent were larger than those over Japan to the NW Pacific.

From the viewpoint of global circulation, the Baiu front was a middle-latitude front which was formed along the zone of great $\nabla T$ between high and low latitudes (Fig. 2). In the lower troposphere, however, the magnitude of $\nabla T$ was relatively small, as compared with that of $\nabla T$ in a typical polar frontal zone. By this, the Baiu front is generally termed a subtropical front (e.g., see Ninomiya, 1984).

Next, $\nabla T$ in and around the eastern Baiu frontal cloud zone is compared with that in the western portion. The Baiu front east of ~130°E (Japan to the NW Pacific) was formed in the zone of maximum $\nabla T$ throughout the troposphere. The Baiu front west of ~130°E (the China continent) was formed to the south of the zone of maximum $\nabla T$ in the upper troposphere, and the magnitude of $\nabla T$ in the lower troposphere of the frontal zone is much smaller than that over the NW Pacific.

The zone of positive vorticity ($\zeta > 0$, Fig. 3) in the lower troposphere (SFC~700 mb) coincided with the Baiu frontal cloud zone. This means that the frontal zone was formed along the north side of the low-level westerly jet (B-jet in this paper), since the zero-line of mean vorticity in the 20°N~40°N latitude zone coincided approximately with the axis of the mean B-jet (the figures are not shown here).

The frontal cloud zone over Japan to the NW Pacific was formed just south of the jet axis at 300 mb. The distance between the 300 mb-jet axis and the zone of maximum Ch amounts (of the Baiu front) increased towards the west. Over the Quinghai-
Xizang Plateau, the distance between them was nearly 1000 km, and the frontal cloud zone was formed in the central region of the upper subtropical anticyclone.

These differences in the thermal and vorticity fields in/around the frontal cloud zone between the continent and Japan to the NW Pacific, affected the structure and behavior of the disturbances related to the Baiu frontal activity, as noted in the later sections.

4. Large-scale structure of the Baiu front

During the analysis period, the large-scale circulation over East Asia, especially around the Baiu front varied with subperiods. In this section, the time change of the Baiu frontal zone will be examined using the 5-day mean fields. Attention will be paid to differences in the vertical structure between active and inactive phases and between two kinds of situations in the active phases.

The left side panels of Fig. 4 show the 5-day mean 500 mb height for Periods 1~6. In the panels, blacked areas indicate the areas of 5-day mean Ch amounts greater than 40%. The zone of maximum Ch amounts, extending into the 30°N~35°N latitude zone, was defined as the Baiu frontal zone during each subperiod. In the right side panels of Fig. 4, the zones of 5-day mean positive vorticity at the 300, 500, 700 and 850 mb levels are superimposed for each subperiod.

The large-scale circulation systems, which had a strong influence on circulation in and around the Baiu frontal zone, were a large-scale cut-off low and a blocking high to the west of the cut-off low (Fig. 4). This large-scale low was located around 100°E/65°N during Period 1 and moved slowly east-southeastward during Period 2 to Period 4 and east-northeastward during Period 5. In association with the movement of the low, Ch amounts and height gradient (\(\nabla Z\)) around the frontal zone changed significantly. In Part I of this study (Akiyama, 1989), Periods 3, 4 and 5 were categorized into active phases and Periods 2 and 6 were inactive phases, respectively. It was already noted in Part I, that baroclinicity (\(\nabla T\)) in the frontal zone during the active phases was greater than that during inactive phases.

As stressed in Section 3, the monthly mean vertical structure of the frontal zone over the NW Pacific differed from that over the continent. The 5-day mean fields also commonly revealed the aforementioned basic difference between the continent and the NW Pacific. The detailed comparison among the active phases (see the panels for Periods 3, 4 and 5 on Fig. 4) revealed, in addition to the aforementioned general features, that the vertical structure...
of the Baiu frontal zone over the area between the east coast (~120°E) of the continent and Japan (~140°E) changed widely with subperiods. The zone of positive vorticity associated with the Baiu front was restricted in the lower troposphere during Periods 3 and 4, while the zone of positive vorticity was formed throughout the troposphere during Period 5. By this, the active phases are further categorized into two types, i.e., the active shallow-type phases (Periods 3 and 4) and the active deep-type phase (Period 5), as shown in Table 1. Figure 5 represents schematically the circulation in and around the Baiu front for the two types of the active phases. A large difference between the two phases lies in the region (40°N~50°N of 110°E~140°E) to north of the Baiu front.

In the active shallow-type phase (Periods 3, 4 of Fig. 4), a large-scale trough is located in 30°N~50°N. Magnitude of VT around the Baiu front is large, compared with that in the active deep-type phase (refer Fig. 4b of Part I). Two low-level positive vorticity zones are formed between
30°N~50°N. The southern one corresponds to the Baiu frontal zone. The northern one is formed below the upper-level positive vorticity zone associated with the upper-level westerly jet, and is clearly separated from the Baiu frontal positive vorticity zone from 110°E to 140°E. The two low-level positive vorticity zones intersect around 150°E, where the upper westerly jet stream (W-jet) approaches the Baiu frontal low-level jet stream (B-jet) to form the deep baroclinic zone over the NW Pacific.

In the active deep-type phase, a blocking high develops in the northern region (40°N~50°N) and the upper westerly jet stream (W-jet) runs along just on the north side of the Baiu frontal zone (right panel of Fig. 5). In the active deep-type phase, another westerly jet stream (HW-jet) runs along the north side of the blocking high. Both jets (W-jet and HW-jet) merge around 150°E. The feature of the frontal zone over the NW Pacific (east of ~150°E) is similar to that over the NW Pacific (east of ~150°E) in the active shallow-type phase. In the following sections, characteristics of the vertical structure of the frontal zone will be described for the active shallow-type phases (Periods 3, 4), the active deep-type phase (Period 5) and the inactive Phases (Periods 2, 6), respectively. Features of the disturbances during these subperiods will be also discussed in relation to the frontal structure.

5. The active shallow-type phases (Periods 3, 4)

Large-scale features in Periods 3, 4

During Periods 3 and 4 (11~20 July, 1982), a large-scale low (trough) is located in 110°E~140°E
Fig. 5. Schematic illustration of the two typical situations of the Baiu front. The left panel is for the active shallow-type phase and the right is for the active deep-type phase. The upper westerly, high-latitude upper westerly and Baiu low-level jets are indicated by the W-jet, the HW-jet and the B-jet, respectively.

Fig. 6. 5-day mean vorticity ($\zeta$) at 300 mb, 500 mb, 700 mb and 850 mb for Period 4 (16~20 July, 1982). The isolines are given with $10 \times 10^{-6}$/sec interval. The areas of 5-day mean vorticity greater than $10 \times 10^{-6}$/sec are hatched. The black areas at 700 mb and 850 mb represent mountains higher than 3000 m and 1500 m, respectively.

/$30^\circ$N~$50^\circ$N (Fig. 4). A zone of positive vorticity ($\zeta > 0$) of $\sim 1000$ km width extends along the north side of the W-jet in $40^\circ$N~$50^\circ$N from Central Asia to the NW Pacific (Fig. 6). This positive vorticity zone is formed throughout the troposphere. In $30^\circ$N~$40^\circ$N between $100^\circ$E and $140^\circ$E, a positive vorticity zone of $\sim 1000$ km width is found only in the lower layer, which corresponded to the Baiu frontal zone.

The Baiu front ($30^\circ$N~$40^\circ$N) In the 5-day mean fields, the magnitude of $\zeta$ in the Baiu frontal zone was great ($\sim 3 \times 10^{-5}$/sec) at
Fig. 7. The positions of positive vorticity maximum $\zeta_{\text{max}}$ at 12-hour intervals during Period 4 are noted with vorticity indexes (Vor. Ind of Table 3), for 300 mb, 500 mb, 700 mb and 850 mb, respectively.

Table 3. Vorticity indexes (Vor. Ind)

<table>
<thead>
<tr>
<th>Vor. Ind</th>
<th>relative vorticity ($\zeta$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$0 &lt; \zeta &lt; 2 \times 10^{-5}$/sec</td>
</tr>
<tr>
<td>2</td>
<td>$2 \leq \zeta &lt; 4$</td>
</tr>
<tr>
<td>3</td>
<td>$4 \leq \zeta &lt; 6$</td>
</tr>
<tr>
<td>4</td>
<td>$6 \leq \zeta &lt; 8$</td>
</tr>
<tr>
<td>5</td>
<td>$8 \leq \zeta &lt; 10$</td>
</tr>
<tr>
<td>6</td>
<td>$10 \leq \zeta$</td>
</tr>
</tbody>
</table>

The northern frontal zone (40°N~50°N)

In the northern latitudes (40°N~50°N), a positive vorticity zone extends along the northern side of the W-jet from Central Asia to the NW Pacific. This positive vorticity zone indicates a deep structure, as seen Fig.6. This zone during Periods 3 and 4 was termed “the northern frontal zone” in this paper. Features of the northern frontal zone differed evidently from features of the Baiu frontal zone in 30°N~40°N. The northern frontal zone was not associated with a significant cloud zone (Fig. 4). The magnitude of $\zeta$ in the northern frontal zone increased with height. The vertical axis tilted slightly southward with height.

In the lower troposphere, the northern frontal zone merged with the Baiu frontal zone at $\sim$150°E (east of Japan). From $\sim$150°E to the east, the Baiu
frontal zone showed a polar frontal structure, as the vertical axis of the positive vorticity zone shifted northward with height.

In the northern frontal zone, a few disturbances propagated from Central Asia to the east (Fig. 7). These disturbances had a deep structure and the magnitude of $\zeta_{\text{max}}$ increased with height. The disturbances developed as they propagated eastward, and $\zeta_{\text{max}}$ reached a maximum magnitude around the east coast of the continent ($\sim 40^\circ\text{N}/120^\circ\text{E}$). Where the height/temperature gradient (i.e., baroclinicity) was intensified by the southeastward movement of the large-scale cut-off low (Fig. 4).

It is noted that the Baiu frontal disturbances began to develop around 120°E, where the northern frontal disturbances reached a maximum intensity. This feature suggests some influence of the northern frontal disturbances on the development of the Baiu frontal disturbances. The destabilization (increase of convective instability) of the Baiu frontal layer due to the upper-level cold advection accompanied by the northern frontal disturbances, and the increased baroclinicity due to the large-scale cut-off low will be two main factors favorable for the development of the Baiu frontal disturbances around 120°E.

Examples of the disturbances and associated cloud systems

Examples of the disturbances and associated cloud systems during Periods 3 and 4 are presented in Fig. 8. The right side maps show cloud distributions represented by TBB (the cloud top temperature measured by GMS-IR) during the 6-day period in Periods 3 and 4. In these maps, ▼ indicates $\zeta_{\text{max}}$ (the maximum of positive vorticity) at 300 mb, and ▲ indicates $\zeta_{\text{max}}$ at 700 mb. N and B indicate the disturbances in the northern frontal zone and those in the Baiu frontal zone, respectively. The left side maps show 500 mb vorticity fields, in which the disturbances ($\zeta_{\text{max}}$) are, also, classified by Labels N and B.

On the TBB maps (Fig. 8), two cloud zones (the northern and the Baiu frontal zones) of several 100s km north-south width are clearly observed. The Baiu frontal zone appears as a nearly continuous cloud zone composed of a row of mesoscale (~1000 km) cloud clusters, while the northern frontal zone is seen as a row of cloud clusters (horizontal scale of ~500 km) separated by cloud-free areas. The Baiu frontal disturbances (labeled by B) developed in association with the mesoscale (~1000 km) cloud clusters. In the Baiu front west of ~140°E, these mesoscale disturbance (▲) were restricted to within the lower troposphere and were not accompanied by any upper-level vorticity maximum (▼).

On the other hand, the low-level disturbances in the northern frontal zone (▲ labeled by N) were always accompanied by the upper-level vorticity maxima ($\nabla$, $\zeta_{\text{max}}$ at 300 mb). That is, the northern frontal disturbances showed deep vertical structures. The mesoscale cloud clusters of the northern frontal disturbances were relatively small, by comparison with those of the Baiu frontal disturbances. This will be due to small moisture content, because they were located in relatively higher latitudes (40°N~50°N).

Some interaction between the northern frontal disturbances and the Baiu frontal disturbances can be inferred from Fig. 8. In the 120°E~140°E area, the Baiu frontal mesoscale disturbances (Bs) were located approximately at the same longitude and at the same time as the northern frontal mesoscale disturbances (Ns). This relationship will be discussed in more detail in Part III of this study.

Around 150°E, the northern frontal zone merged with the Baiu frontal zone and formed a "deep-type" baroclinic Baiu frontal zone. The disturbances in the Baiu frontal zone east of 150°E developed throughout the whole troposphere.

6. The active deep-type phase (Period 5)

Large-scale features in Period 5

Large-scale features during Period 5 are characterized by the northeastward movement of the large-scale cut-off low and the development of a blocking ridge at ~45°N/120°E (Fig. 4). In association with the development of the blocking ridge, the upper westerly jet stream in 40°N~50°N over Central Asia was split into two branches. In 100°E~140°E, the upper westerly jet (W-jet) and the high-latitude westerly jet (HW-jet in Fig. 5) extended along the south side and the north side of the ridge, respectively. With the change in the large-scale circulation, the situation in the vicinity of the Baiu frontal zone showed a significant change as described below.

Structure of the Baiu frontal zone

Figure 9 shows the 5-day mean vorticity maps at 850 mb, 700 mb, 500 mb and 300 mb for Period 5 (21~25 July 1982). Over the continent in 30°N~40°N, a low-level positive vorticity zone of ~1000 km width extends northeastward from the eastern foot of the Quinghai-Xiangze Plateau to the east coast (~35°N/120°E) of the continent. This zone coincided with the Baiu frontal cloud zone. That is, in 100°E~120°E, the Baiu frontal positive vorticity zone was formed only in the lower layer (a shallow structure).

The Baiu frontal positive vorticity zone "intersected", on the horizontal projection, with the upper-level positive vorticity zone associated with the westerly jet stream (W-jet) at ~35°N/120°E. From the "intersection" area to the east, the positive vorticity zone of the Baiu front was formed throughout the troposphere (the deep-type structure). In
Fig. 8. Examples of the active shallow-type Baiu front during the six-day period from 12GMT 13 to 00GMT 19 July 1982. The right and left panels are TBB latitude-longitude diagrams and 500 mb vorticity (ζ) maps, respectively. In TBB maps, the isotherm interval is 10°C. The symbols ▼ and ▲ represent the positions of the vorticity maximum ζ_{max} at 300 mb and 700 mb, respectively. In 500 mb vorticity maps, the isolines are given with $10^{-6}$/sec interval. The areas of vorticity greater than $10^{-6}$/sec are hatched. The disturbances in the Baiu frontal zone (30°N~40°N) and in the northern frontal zone (40°N~50°N) are noted by B and N, respectively.

120°E~150°E, the Baiu frontal zone exhibited a structure as a polar front; that is, the vertical axis of the positive vorticity zone shifted northward with height, from ~35°N at 850 mb to ~40°N at 300 mb. However, differing from the typical polar front, the upper-level westerly was very weak in 30°N~40°N and the magnitude of ζ (~$2\times10^{-5}$/sec) was nearly equal throughout the troposphere in the Baiu frontal zone.

Features of the Baiu frontal disturbances
Figure 10 shows the positions of ζ_{max} at 12-hour
Fig. 9. As in Fig. 6, but for Period 5 (21~25 July, 1982).

Fig. 10. As in Fig. 7, but for Period 5.
interval at 850 mb, 700 mb, 500 mb and 300 mb during Period 5. The magnitude of $\zeta_{\text{max}}$ is given by the vorticity index (Vor. Ind) defined in Table 3. Features of the frontal disturbances also changed with the change of the frontal structure. Some disturbances (vortices) developed in the lower layer of the Baiu front around the eastern foot of the Qinghai-Xizang Plateau. A few of the shallow disturbances propagated northeastward on the frontal zone, and developed at the “intersection”. The magnitude of the positive vorticity ($\zeta_{\text{max}}$) reached a maximum around 120°E~130°E. The maximum value of $\zeta_{\text{max}}$ was $\sim 8 \times 10^{-5}$/sec in the lower layer (Fig. 10). This value was larger than that during the shallow-type periods. This indicates that the Baiu frontal disturbances in the lower layer tended to develop during the deep-type baroclinic period.

At 300 mb, the positive vorticity zone associated with the W-jet extended along the northern rim of the Qinghai-Xizang Plateau. A few disturbances propagated from the west in this zone. They began to develop around the northeastern corner of the Plateau and reached a maximum value of positive vorticity around the “intersection” area ($\sim 35°N/120°E$).

It is a notable fact that the remarkable development of the disturbances in the W-jet and B-jet occurred around the “intersection” area. This fact supports the view that the evolution of the Baiu frontal disturbances from the shallow structure over the continent into the deep structure over the “intersection” area can be attributed to coupling with the upper disturbances in the W-jet.

Examples of the disturbances and associated cloud systems

The right side and left side maps of Fig. 11 show cloud (TBB) distributions and evolution of disturbances in 500 mb vorticity field during the active deep-type phase, respectively. The mesoscale systems identified at 12 GMT 22 July were labeled by $\alpha$, $\beta$ and $\gamma$. The evolution of these disturbances $\alpha$, $\beta$ and $\gamma$ was examined on 12-hourly vorticity maps of 850 mb, 700 mb, 500 mb and 300 mb for the successive four days in Period 5.

On the $T_{BB}$ maps, the Baiu frontal zone appears as the wavy cloud zone of several 100s km width. Several mesoscale (~1000 km) cloud clusters are found in the wavy cloud zone. Associated with the cloud clusters, low-level mesoscale vorticity maxima ($\Delta\alpha$) are found throughout the whole frontal zone (90°E~160°E), while the upper-level ones ($\nabla\gamma$) are seen only east of 120°E. This indicates that the Baiu frontal mesoscale disturbances were shallow in 90°E~120°E and that they became disturbances with a deep structure around 120°E.

By examining the evolution of the disturbances $\alpha$, $\beta$ and $\gamma$ in Fig. 11, it is found that the associated mesoscale cloud clusters changed significantly in shape and extension with time as they propagated slowly eastward. It is an important fact that the vertical structure of the mesoscale disturbances changed even in “the deep structure stage”. That is, the position of the upper-level $\zeta_{\text{max}}$ ($\Delta\alpha$) relative to that of the low-level $\zeta_{\text{max}}$ ($\nabla\gamma$) changed with time. The mesoscale cloud clusters tended to develop when the center of the low-level vorticity maximum was located southeast of that of the upper-level vorticity maximum.

The high-latitude zone (50°N~60°N)

During Period 5, the upper westerly jet stream in 40°N~50°N was split into two branches over Central Asia, in association with the development of the blocking ridge. The northern branch (HW-jet) extended along the north side of the blocking ridge, and thus another positive vorticity zone was formed in 50°N~60°N along the north side of the HW-jet. In this zone, the magnitude of $\zeta_{\text{max}}$ increased with height and reached $5~6 \times 10^{-5}$/sec at 300 mb. However, the vertical axis of this positive vorticity zone was not tilted with height. In this zone, the movement of the disturbances was very slow and the magnitude of $\zeta_{\text{max}}$ increased with height (Fig. 10). This zone bent southeastward at the eastern side of the blocking ridge, and merged with the Baiu frontal zone around 150°E. From ~150°E to the east (over the northwest Pacific), the Baiu frontal zone showed a polar-front type vertical structure.

7. The inactive phases (Periods 2 and 6)

As an example of the inactive phases, features in Period 2 (6~10, July 1982) are studied in detail. The height gradient ($\nabla Z$) at 500 mb in 30°N~40°N during the inactive phase is significantly smaller than that during the active phases (Fig. 4a). The Baiu frontal zone (the zone of the positive vorticity over the Japan Islands) showed a deep-type barotropic structure (that is, the vertical axis of the vorticity zone was not tilted northward with height and the positive vorticity zone was formed throughout the troposphere).

On the 5-day mean vorticity maps (Fig. 12) of Period 2, the upper-level positive vorticity zone along the W-jet was separated from the Baiu frontal zone, around the northeastern corner of the Qinghai-Xizang Plateau, by a zone of negative vorticity. However, some of the disturbances which propagated from the west in the W-jet moved southeastward from the northeastern corner of the Plateau to the Baiu front. These disturbances developed in the Baiu front east of ~115°E/35°N. As seen in Fig. 13, the magnitude of $\zeta_{\text{max}}$ at the upper level was greater than that in the lower layer. The magnitude of $\zeta_{\text{max}}$ in Period 2 was smaller than that in the active deep-type phase (Period 5).
There was a positive vorticity zone in the high latitude (50°N~60°N) between 100°E and 160°E. The vertical axis of this zone was not tilted with height (Fig. 12). Some of the disturbances propagated from the west along the north side of the Qinghai-Xizang Plateau and moved slowly northeastward in the high-latitude positive vorticity zone. In this zone, space-time changes of the disturbances were generally small.

During Period 6, space-time changes of the disturbances were generally small (figures are not shown). The movement of the disturbances on the Baiu frontal zone was very slow and the magnitude of $\zeta_{\max}$ did not change much with time. The magnitude of $\zeta_{\max}$ increased with height. The magnitude of $\zeta_{\max}$ in Period 6 was smaller than that in Period 5 (an active deep-type phase).

8. Features of the disturbances in/around the Baiu front

In the previous sections, features in subperiods of July 1982 were described. In the present sec-

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**Fig. 11.** As in Fig. 8, but for the active deep-type Baiu front during the three-day period of 12GMT 22, July to 12GMT 25, Jul 1982. The evolution of the Baiu frontal mesoscale disturbances indicated by $\alpha$, $\beta$ and $\gamma$ is shown in TBB maps and 500 mb vorticity maps, respectively.
Fig. 12. As in Fig. 6, but for Period 2 (06~10 July, 1982).

Fig. 13. As in Fig. 7, but for Period 2.
where the maximum of positive vorticity and the minimum of height were in phase.

At 850 mb, over the continent (grid point NO 5), positive vorticity was basically prevailing. Synoptic-scale period variations were obscure over the continent and the variations gradually increased toward the east. The amplitude in the lower layer is smaller than that in the upper layer.

Mesoscale period variations

At 200 mb, the amplitude of mesoscale period variations was small over the continent (grid point NO 5). The amplitude increased toward the east. The mesoscale variations were most evident around 130°E (NO 15) and the amplitude of vorticity reached \( \sim 4 \times 10^{-5} \) sec. However, the maximum amplitude of the mesoscale variations was much smaller than that of the synoptic-scale ones.

At 850 mb over the continent, one-day period (mesoscale) variations with small amplitude were superimposed on the basic positive vorticity field. The prominent mesoscale period changed from one day to a few days toward the east. Around 140°E (grid point NO 21), the mesoscale period of a few days was prevailing. The amplitude of the mesoscale variations increased toward the east (NO 15, NO 21) and reached a maximum in 130°E–140°E.

b. Features in the 40°N~50°N latitude zone

Features of the time series at the western grid point (NO 1, \( \sim 100°E \)) largely differ from those at the eastern grid point (NO 19, 140°E). This indicates a great change in the disturbances during their eastward propagation. The time series of Fig. 15 also show large differences among subperiods due to the passage of the large-scale cut-off low. A large minimum of height and a large peak of positive vorticity observed during Period 3 through Period 4 at 850 mb and 200 mb in the time series at grid point NO 7 indicate the passage of the cut-off low (Fig. 4). Although prominent periods and amplitudes of the disturbances changed with time, the following general features are pointed out.

Synoptic-scale period variations

At 200 mb, the synoptic-scale period variations were small over the mainland of the continent (grid point NO 1, \( \sim 100°E \)). They were amplified toward the east. At grid point NO 19 (140°E), the synoptic-scale variations were most evident.

At 850 mb, inland (grid point NO 1), synoptic-scale period variations were obscure. They were amplified toward the east, and reached a maximum around Japan (NO 19, 140°E). That is, synoptic-scale period disturbances developed throughout all troposphere during their eastward-propagation of \( \sim 3000 \) km distance from \( \sim 100°E \) to \( \sim 140°E \).
Mesoscale period variations

At 200 mb, one to a few-day period variations were predominant in 100°E~120°E. The amplitude of the mesoscale variations decreased toward the east, and the mesoscale variations became very small around 140°E (NO 19).

At 850 mb, the mesoscale period variations were observed through the grid points. The prominent period became longer toward the east, from one day in the inland area of the continent to a few days around the east coast of the continent. The
amplitude of the mesoscale variations reached a maximum around the east coast of the continent (110°E~120°E, grid points 2, 7).

In short, the synoptic-scale period disturbances began to develop around the east coast (~120°E) of Asian Continent in 30°N~50°N. The mesoscale period disturbances tended to develop in 100°E~120°E of 40°N~50°N and in 120°E~140°E of the Baiu front. It was pointed out in Section 3, that the baroclinicity in the Baiu frontal zone was intensified by the confluence of the W-jet with the B-jet around the east coast of the continent (Fig. 3). This will cause the development of the Baiu frontal mesoscale disturbances around 120°E.

9. Concluding remarks

Part II of this study described inclusively the structure of the Baiu frontal zone and features of the frontal disturbances in July 1982, analyzing mainly relative vorticity fields. Special attention was paid on relationship between the upper westerly jet (40°N~50°N) and the Baiu low-level jet (30°N~40°N). The former (W-jet) had strong influence on the structure of the Baiu front and features of the disturbances in around the Baiu front. From the vertical structure of the Baiu front and high-cloud (Ch) amounts in the frontal zone, three situations (phases) of the Baiu front, i.e., active shallow-type, active deep-type and inactive phases, were classified. Characteristics of the frontal structure and features of the disturbances in around the frontal zone were examined for these three phases, respectively. Results are summarized as follows.

(1) In monthly mean fields of the analysis period, the Baiu frontal cloud zone coincided with a low-level positive vorticity zone along the low-level jet (B-jet). In the Baiu front over the continent, the positive vorticity was confined to the lower layer. The Baiu frontal zone was merged with the upper westerly jet around the east coast (~120°E) of the continent. From the coastal area to the east (Japan and the NW Pacific), the Baiu front showed a baroclinic structure (the positive vorticity zone was formed throughout the troposphere and the vertical axis of the positive vorticity zone tilted northward with height). The large-scale baroclinicity in the region from the east coast to the NW Pacific in 30°N~50°N was greater than the inland of the continent. This accounts for the development of the Baiu frontal disturbances in this region and the difference in cloud features of mesoscale systems between the western (over the continent) Baiu front and the eastern (over Japan—the NW Pacific) Baiu front pointed out in Part I.

(2) During active shallow-type phases, the large-scale trough located in 110°E~140°E/30°N~50°N. The positive vorticity zone of the Baiu front (in 30°N~40°N, associated with the B-jet) was formed only in the lower troposphere. Another positive vorticity zone (the northern frontal zone) associated with the W-jet was formed throughout the troposphere in 40°N~50°N. Shallow and deep mesoscale disturbances developed in the Baiu front and in the northern front, respectively. They were located simultaneously at nearly the same longitude. This feature indicates some interaction between the Baiu frontal shallow disturbances and the northern frontal deep disturbances.

(3) During an active deep-type phase, a large-scale blocking ridge located at ~50°N/120°E split the upper westerly flow into two westerly jets (W-jet and HW-jet). The southern positive vorticity zone associated with the W-jet at ~35°N/120°E, where to the east the Baiu front showed a deep and baroclinic structure. The low-level mesoscale shallow disturbances propagated from the continental inland area in the Baiu front coupled with the upper-level mesoscale disturbances in the W-jet around the “intersection”, and developed into the deep disturbances.

(4) During inactive phases, the thermal and height gradients were weak in around the Baiu frontal zone. The vertical structure of the positive vorticity zone of the Baiu front showed a deep and barotropic one (the vertical axis was not tilted). The Baiu frontal disturbances were not intense.

Space-time scale and structures of the disturbances described in Part II will be examined statistically in Part III of this study, by means of spectral analysis.

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References

1982年7月の梅雨前線の大規模・総観規模および中規模的変動

Part II: 前線带の構造と擾乱

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Part Iでは静止衛星赤外データにもとづき、1982年7月の梅雨前線上の雲変動を解析した。Part IIでは、同期間の前線帯の垂直構造を上層jetと下層jetとの関係で議論し、また前線帯の雲変動に関連した擾乱の挙舞を相対湿度場で解析した。結果を以下に要約する。

解析期間（二ヶ月間）の平均場でみると、前線の雲層はチベット高原南縁から東へ伸びる下層jet（梅雨jet）北側の正圧度帯と一致する。一方チベットの北縁を回る上層jet(westerly-jet)は、大陸の東岸（〜120°E）以東で南下し、日本列島近傍では前線帯の北側に沿う。〜120°E以東の梅雨前線帯の正圧度帯は対流層全域に存在し上層に向かって北へ傾斜しており、梅雨前線帯が傾圧帯であることを示している。大陸では、梅雨前線の下層jetと上層jetは南北に約1500 km離れ、梅雨前線帯の正圧度帯は下層にのみみられ、この大陸と日本列島上の前線帯の構造の違いは、Part Iで指摘した両者間の中規模雲システムの様相の相違を説明する。

大規模の前線の変動に伴って梅雨jetと上層jetとの関係は変動し、120°E〜140°Eの梅雨前線の雲量・前線の垂直構造・前線帯の擾乱（低気圧）の様相も変動した。雲量と前線帯の構造から、梅雨前線を三つの状況((1)active-deep phase, (2)active-shallow phase, (3)inactive phase)に分類し、それぞれのphaseの前線帯の構造と擾乱の特徵を記述した。

結論として、日本近傍の梅雨前線上の中規模擾乱は、(1)では上層ほど軸の西へ傾く背の高い構造であること、(2)では背の低い構造で北側（上層jetに伴う）前線上の背の高い擾乱の南側に位置して発達していったことを示した。またいずれのactive phasesでも、梅雨前線上の中規模擾乱は大陸東岸（〜120°E）で発達し始め、その発達に上層jet内を中央アジアから移動して来る擾乱が大きく関わっていることを見出した。

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