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

Part III: Space-Time Scale and Structure of Frontal Disturbances

By Takako Akiyama

Meteorological Research Institute, Tsukuba 305, Japan

(Manuscript received 30 June 1989, in revised form 20 September 1990)

Abstract

Part I of this study examined the large-scale situations and cloud variations of the Baiu front during July 1982, and showed that the large-scale increases of baroclinicity around the front and the low-level southerly wind toward the front contributed to the increase of cloud amounts in the frontal zone (the active phase). The regional difference in the cloud variations of mesoscale periods was also described.

In Part II, the vertical structure of the Baiu front, features of disturbances in/around the Baiu frontal zone were studied for the six 5-day subperiods of July 1982, based on the relative vorticity fields. The results showed that during the active phases the Baiu frontal mesoscale disturbances tend to develop at $\sim 120^\circ\text{E}$, under the influence of the disturbances in the upper westerly jet.

In Part III, the space-time scale and structure of the disturbances in/around the Baiu front are examined by spectral analysis mainly on the relative vorticity fields. The interaction between the disturbances in the Baiu front and in the upper westerly jet is also examined. The results of Part III are summarized as follows.

From spectral analysis, the disturbances of a synoptic-scale (~ 6 -day) and three mesoscale (~ 3.5 -, ~ 2.5 -, 1-day) periods are found in/around the Baiu front. These disturbances developed through interaction between them, and showed a complicated evolution process.

Many shallow-weak vortices were generated around the Quinghai-Xizang Plateau with 1-day period. Some of them in the Baiu front ($30^\circ\text{N}\sim 40^\circ\text{N}$) propagated east along the low-level Baiu jet (B-jet) and began to develop into the long-lived mesoscale disturbances around the east coast ($\sim 120^\circ\text{E}$) of the continent.

In the period when a synoptic-scale disturbance in the upper westerly jet (W-jet; in $40^\circ\text{N}\sim 50^\circ\text{N}$) developed around 120°E (the active-shallow Baiu front), the aforementioned weak vortices developed into the Baiu frontal shallow mesoscale (~ 2.5 -day period) disturbances, making pairs with the deep mesoscale (~ 2.5 -day period) disturbances propagated from the west in the W-jet. Some of the shallow and the deep mesoscale disturbances developed as subsystems of one synoptic-scale disturbance.

In the period when the Baiu front east of $\sim 120^\circ\text{E}$ showed a baroclinic structure (the active-deep Baiu front), the aforementioned shallow-weak vortices in the B-jet developed into the Baiu frontal deep mesoscale disturbances with a period of ~ 3.5 days, coupling with the upper-level mesoscale (~ 3.5 -day period) disturbances propagated from Central Asia in the W-jet.

Although the period, vertical structure and evolution process of these mesoscale frontal disturbances differed from each other in accordance with the large-scale and/or synoptic-scale frontal situations, they caused the cloud variations of mesoscale periods in the frontal zone.

1. Introduction

A subtropical stationary front, which is termed "Baiu front" in Japan, is formed in $30^\circ\text{N}\sim 40^\circ\text{N}$ from the northwest Pacific to the Quinghai-Xizang Plateau through Japan in June~July. The Baiu front is a quasi-stationary large cloud zone of ~ 1000

km north-south width.

Some papers (*e.g.*, see Akiyama, 1973; Kato, 1985; Ninomiya and Muraki, 1986) investigated the large-scale features of the Baiu front on the mean fields of 5-day or 10-day. In these studies, however, neither the frontal structure throughout the whole frontal zone (from the NW Pacific to China Continent), nor the difference in the structure between

the active and inactive Baiu fronts, has been fully discussed.

Some studies (*e.g.*, see Matsumoto *et al.*, 1970; Ninomiya and Akiyama, 1971, 1974; Akiyama, 1978) revealed the mesoscale (~ 1000 km) features of the Baiu front and/or the day-to-day variations of the frontal activity (rain/clouds), in relation to the disturbances (lows) developed in the frontal zone.

Yoshizumi (1977, 1978) studied, by composite and/or harmonic analysis methods, the structures of the mesoscale disturbances developed over Japan in the Baiu season, mainly in the height and temperature fields. However it was questionable whether the analyzed disturbances developed in the Baiu frontal zone, since the position of the Baiu frontal cloud zone was not mentioned. In addition, the structure of the Baiu frontal mesoscale disturbances obtained by statistical treatment on the height and temperature fields was unreliable, because, according to the results of spectral analysis in the present study, the vertical and horizontal coherences in the disturbances in these fields are much smaller than those for the vorticity field.

It has been shown that many vortices were generated over the Quinghai-Xizang Plateau in the summer monsoon and some of them caused heavy rainfall over Central China (*e.g.*, see Tao and Ding, 1981). Murakami and Huang (1984) showed, by composite analysis, the structure of mesoscale (about 1000 km) vortices which were generated around the Quinghai-Xizang Plateau in the summer rainy season. In these studies, however, the relationship between these vortices and the Baiu front has not been described clearly.

Ninomiya *et al.* (1981) and Akiyama (1984a, b), in their studies on the evolution process of a mesoscale long-lived cloud cluster which was generated at the eastern foot of the Quinghai-Xizang Plateau and moved eastward in the Baiu front, pointed out that the cluster sustained its long life under the influence of an upper short-wave trough approached from northwest to the cluster. Ma and Bosart (1987), in a case study on a heavy rainfall event occurred in a quasi-stationary front (the Baiu front) of South China, also pointed out that a short-wave trough north of the Quinghai-Xizang Plateau and a very weak short-wave trough south of the Plateau played important roles on the event.

To understand further the Baiu front, it is necessary to examine space and time variations of cloud/rainfall in the frontal zone, and to clarify features of the disturbances developed in and around the whole Baiu front throughout the China Continent to the Northwest Pacific. In Part I of this study (Akiyama, 1989), the space and time variations of cloud in the Baiu frontal zone were studied. Part II of this study (Akiyama, 1990) described the time change of the frontal structure and features of

the frontal disturbances for the six 5-day subperiods of the analysis period (July, 1982), analyzing mainly the relative vorticity fields. The space and time variations of the disturbances in/around the Baiu frontal zone were also examined on the time series of vorticity throughout July 1982. Some important results of Parts I and II will be summarized in Section 3.

The purpose of Part III is to demonstrate features and vertical structures of the synoptic-scale and mesoscale (see definitions in Table 1) disturbances in and around the Baiu front over East Asia to the NW Pacific, by means of spectral analysis. Attention will be paid to prominent scales of the disturbances, appearance zones of these disturbances, interaction between the Baiu frontal disturbances (in $30^{\circ}\text{N}\sim 40^{\circ}\text{N}$) and the disturbances in the upper westerly zone (in $40^{\circ}\text{N}\sim 50^{\circ}\text{N}$) and the relationship between the synoptic-scale and mesoscale disturbances. Section 3 describes an overview of the analysis period. In Section 4 prominent periods of the disturbances will be examined by spectral analysis. Section 5 presents the evolution and structure of synoptic-scale period (~ 6 -day) disturbances. In Section 6, three mesoscale period (~ 3.5 -day, ~ 2.5 -day, 1-day) disturbances are examined. Section 7 gives summary and remaining problems.

2. Data and procedure of the analysis

Main upper data used in the present study are 12-hourly grid point values of Fine Mesh Analysis (FANAL) Data at the 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.

The disturbances will be examined mainly on the relative vorticity fields, for the reason explained in Part II of this study. Relative vorticity (ζ) is abbreviated as "vorticity" hereafter. Spectral analysis is applied to the time series of vorticity at every grid point within the analysis domain and then the disturbances with periods of high spectral density are examined.

3. Overview of the analysis period

The relationship between the Baiu frontal cloud zone and the positive vorticity zone in one-month (July, 1982) mean fields will be examined briefly. Figure 1 shows 31-day mean (July, 1982) high-cloud (Ch, cloud top higher than the 400 mb level) amounts. 31-day mean and standard deviation (SD) of vorticity (ζ) at 300 mb and 700 mb are presented in Fig. 2. The zone of the maximum Ch amounts with a width of ~ 800 km extended in $30^{\circ}\text{N}\sim 40^{\circ}\text{N}$ was defined as the Baiu frontal zone in this study.

Table 1. Explanation of the time-scales used in this paper.

large-scale	longer than ~ 6 days
synoptic-scale	~ 6 -day period
mesoscale	one to 2 ~ 3 -day period

Fig. 1. 31-day (1 $\sim$ 31 July, 1982) mean high-cloud (Ch) amounts. The stippled and black areas represent the areas of high-cloud amounts greater than 40 % and 50 %, respectively. The Ch data are analysed in the region bounded by a thick line.

This zone coincided approximately with the low-level positive vorticity zone of ~ 1000 km width, which was formed along the north side of the low-level Baiu jet (B-jet).

At the upper level, a positive vorticity zone of ~ 1000 km width in $40^{\circ}\text{N}\sim 50^{\circ}\text{N}$ (to the north of the Qinghai-Xizang Plateau) extended between 70°E and 110°E , and further extended east of $\sim 110^{\circ}\text{E}$ (the eastern coast of the continent to the NW Pacific) in $35^{\circ}\text{N}\sim 45^{\circ}\text{N}$. This zone was formed along the north side of the upper westerly jet stream (W-jet). The Baiu frontal cloud zone over Japan to the NW Pacific extended along the south side of the W-jet. The distance between the Baiu frontal cloud zone and the W-jet increased toward the west. The distance between them became ~ 1000 km around the Qinghai-Xizang Plateau. The magnitude of positive vorticity in the upper-level zone was much greater than that in the low-level zone.

Features of large-scale circulations, frontal structures and cloud distributions showed complicated changes during July 1982 as described in Parts I and II of the this study. The most significant changes in the large-scale circulations over East Asia were accompanied by the passage of a large-scale cut-off low in $40^{\circ}\text{N}\sim 55^{\circ}\text{N}$. Under the influence of the

cut-off low, the Baiu front was activated in 11 $\sim$ 25 July 1982. Part II, further, demonstrated two typical phases of the active Baiu front; *i.e.*, the active shallow-type and the active deep-type Baiu front. The large-scale situations in these phases are illustrated in Fig. 3.

In Parts I and II, it was also shown that the synoptic- and meso-scale disturbances developed in the Baiu front ($30^{\circ}\text{N}\sim 40^{\circ}\text{N}$) and the northern front ($40^{\circ}\text{N}\sim 50^{\circ}\text{N}$, see Fig. 15 of Part II) during the analysis period. Spectral analysis of Ch amounts in Part I revealed the following features: over the continent, the synoptic-scale (~ 6 -day period) variations are relatively small, and the mesoscale variations with 1-day period are evident. Over the NW Pacific, the synoptic-scale variations are evident and the mesoscale variations with periods of ~ 3.5 and ~ 2.5 days are superimposed on the synoptic-scale variations. Around the Japan Islands, the synoptic- and meso-scale variations in the Baiu frontal zone showed the transitional features between the western (China Continent) and the eastern (the NW Pacific) parts of the Baiu front (see Figs. 10 and 11 of Part I).

The time series data of vorticity and geopotential height at 200 mb and 850 mb at several grid points in the Baiu front and the northern frontal zone also showed the following features: the variations with 1-day period are most evident over the continent, while the variations with synoptic-scale and 2 ~ 3 -day mesoscale periods increased their amplitude as they propagated eastward.

The areas of large standard deviation (SD) of vorticity at 300 mb and 700 mb (Fig. 2) indicate the areas where the disturbances are active. SD in the Baiu frontal zone ($30^{\circ}\text{N}\sim 40^{\circ}\text{N}$) from 120°E to 150°E was large throughout the troposphere, while SD in the Baiu frontal zone over the continent was relatively small. In $40^{\circ}\text{N}\sim 50^{\circ}\text{N}$, SD was large around the eastern coast ($\sim 120^{\circ}\text{E}$) of the continent. Of course, the areas where the disturbances developed, coincided with the areas of large SD value. Power spectral density of vorticity is also large in these large SD areas, because the spectral density is computed from covariance of vorticity variations.

Keeping the aforementioned overview in mind, we will discuss the results of spectral analysis of the vorticity field in the following sections.

4. Prominent periods of the disturbances

The analysis in Part II indicated that the disturbances in $40^{\circ}\text{N}\sim 50^{\circ}\text{N}$ (the northern frontal zone) have a strong influence on the Baiu frontal disturbances in $30^{\circ}\text{N}\sim 40^{\circ}\text{N}$. To survey prominent periods of the disturbances in these two zones, the diagrams of power spectral density for vorticity at the grid points indicated by Δ in Fig. 4 are presented in Fig. 5.

Fig. 2. 31-day (1~31 July, 1982) mean (upper panels) and SD (standard deviation, lower panels) of vorticity (ζ) at 300 mb (right side) and 700 mb (left side). The isoline intervals are 5×10^{-6} /sec. The areas of 31-day mean vorticity greater than 5×10^{-6} /sec are shaded. The areas of SD greater than 15×10^{-6} /sec for 700 mb and greater than 30×10^{-6} /sec for 300 mb are also shaded. The thick broken line represents the position of the Baiu front (the zone of maximum Ch amounts). The black areas at 700 mb present mountains higher than 3000 m.

a. Features in the Baiu front

Three peaks of high spectral density are commonly found at ~ 6 -day (synoptic-scale), ~ 3.5 -day (mesoscale) and ~ 2.5 -day (mesoscale) periods through the diagrams of Fig. 5a. As noted in Part I, these prominent periods were also found in the time series of Ch amounts in the Baiu front during the analysis period. The peak values of the high spectral density changed greatly from diagram to diagram (from longitude to longitude and from level to level). Although the changes of these disturbances were complicated, the following features are pointed out:

(1) Spectral density of the synoptic-scale period (~ 6 -day) is relatively small over the continent and increased toward the east, especially in the upper layer.

(2) The peaks of the mesoscale period of ~ 3.5 days are evident over the continent. They are, however, not evident over Japan, as seen on the diagrams of NO 15 ($\sim 33^\circ\text{N}/130^\circ\text{E}$), NO 18 ($\sim 34^\circ\text{N}/135^\circ\text{E}$)

and NO 21 ($\sim 35^\circ\text{N}/140^\circ\text{E}$). As noted in Section 6, features of the disturbances with ~ 3.5 -day period changed greatly in space and time.

(3) Spectral density of the mesoscale period of ~ 2.5 days is also small over the continent and increases toward the east, especially in the lower layer. In the diagram of NO 21 ($\sim 35^\circ\text{N}/140^\circ\text{E}$), spectral density at ~ 2.5 -day period is large in the lower layer and is comparable with that of the synoptic-scale period.

(4) Spectral density of 1-day period is significantly large over the inland of the continent, especially around the Quinghai-Xizang Plateau (not shown in Fig. 5).

b. Features in $40^\circ\text{N} \sim 50^\circ\text{N}$

As seen in Fig. 5b, three peaks of high spectral density are also found at ~ 6 -, ~ 3.5 - and ~ 2.5 -day periods. The following features are pointed out:

(1) Spectral density around the synoptic-scale period (~ 6 -day) increases toward the east in the whole

Fig. 3. Schematic illustration of the two typical situations of the Baiu front (see Section 4 of Part II). W-jet, HW-jet and B-jet present the upper westerly, high-latitude upper westerly and low-level Baiu jets, respectively.

troposphere. This indicates that the synoptic-scale disturbances developed propagating eastward.

(2) A large peak of high spectral density is found at ~ 3.5 -day period in the diagram of NO 1 (110°E). However, the period of the spectral peak around 3.5-day period changed significantly with longitude and level.

(3) Spectral density of the mesoscale period of ~ 2.5 days at the upper levels is nearly equal through the diagrams (NO 1, 2, 7, 12, 19), while that at the lower levels reaches a maximum around the east coast of the continent ($\sim 120^\circ\text{E}$) and becomes obscure toward the east.

(4) Spectral density of 1-day period is also significantly large around the northern area of the Quinghai-Xizang Plateau (figures are not shown).

From the analysis in the present section, it is concluded that the disturbances with these four kinds of periods (~ 6 -, ~ 3.5 -, ~ 2.5 - and 1-day) are promi-

Fig. 4. The analysis domain for FANAL data in this study. The symbol Δ labeled by NO 1, 2, 7, 12, 19 (in $40^\circ\text{N}\sim 50^\circ\text{N}$) and NO 5, 10, 15, 18, 21 (in the Baiu front) presents the position of grid points, respectively. Results of spectral analysis at these grid points are shown in Fig. 5.

nent during the analysis period. In the following sections, features of these disturbances will be examined in more detail.

5. Features of synoptic-scale period (~ 6 -day period) disturbances

The behavior and vertical structure of ~ 6 -day period disturbances will be examined in detail.

Spatial variations

Spectral density at 5.86-day period was calculated on every grid point for the 300 mb, 500 mb, 700 mb and 850 mb vorticity fields. Phase was also calculated for each level, as centered at one of the grid points with high spectral density. As examples, spatial distributions of the density and the phase at 300 mb and 700 mb are shown in Fig. 6.

At 300 mb, a high density zone with ~ 1000 km north-south width extends along the northern rim of the Quinghai-Xizang Plateau over Central Asia. Then the high-density zone extends southeastward up to the Baiu frontal zone. From the eastern coast of the continent to the NW pacific, the high-density zone spreads widely in $30^\circ\text{N}\sim 50^\circ\text{N}$. The magnitude of density in the zone reaches a maximum over Japan (in $30^\circ\text{N}\sim 40^\circ\text{N}$ of $130^\circ\text{E}\sim 140^\circ\text{E}$). This feature indicates that the waves with north-south width of ~ 1000 km propagated from Central Asia in the upper westerly zone (see Fig. 2) developed into the large waves of ~ 2000 km width around the east coast. The wavelength/phase-speed and the propagation direction of these waves differ in latitude and longitude, as indicated by the phase lines in Fig. 6. The phase line presents a "hooked-shape" propagation pattern around 130°E to the east, where the

Fig. 5a. Power spectral density diagrams of vorticity (ζ) at the standard levels (200 mb~SFC) on the grid points in the Baiu front (NO 5, 10, 15, 18, 21 in Fig. 4). The range of period from 8.20 days (frequency 0.122 day^{-1}) to 2.05 days (0.488 day^{-1}) is shown in the diagrams.

Fig. 5b. As in Fig. 5a, but for the grid points in $40^{\circ}\text{N}\sim 50^{\circ}\text{N}$ (NO 1, 2, 7, 12, 19 in Fig. 4).

wavelength is ~ 3000 km.

At 700 mb (Fig. 6), a zone of high spectral density extends southeastward from $\sim 90^{\circ}\text{E}/60^{\circ}\text{N}$ along the northern periphery of the Mongolian Plateau. Another zone of high density extends along the Baiu

front (the north side of the B-jet in Fig. 3). As indicated by the phase lines in Fig. 6, the southern zone along the B-jet merges with the northern zone around the east coast ($\sim 120^{\circ}\text{E}$) of the continent, where the waves began to be amplified in the upper

Fig. 6. Spatial distributions of power spectral density (thin lines) of vorticity (ζ) at 5.86-day period at 300 mb (upper panel) and 700 mb (lower panel). The isolines of density are given with $50 \times 10 \times (10^{-6}/\text{sec})^2$ day interval. The thick lines indicate the phase centered at one of the grid points with high spectral density. The black circles present the position of the grid points S1~S7. The thick broken line presents the position of vertical section of Fig. 11. The black areas in the 700 mb map show mountains higher than 3000 m.

layer. From the coast ($\sim 120^\circ\text{E}$) toward the east, the wave propagation pattern is similar to that in the upper layer, although the magnitude of spectral density is small in the lower layer. (The high-density areas observed in $20^\circ\text{N} \sim 30^\circ\text{N}$ on the 700 mb map of Fig. 6 are attributed not to the Baiu frontal disturbances, but to tropical depressions in the analysis period.)

Spatial distribution of spectral density of 500 mb mixing ratio (q) at 5.86-day period is presented in Fig. 7. Phase lines are also shown in Fig. 7. The large spectral density is seen along the Baiu frontal zone. Spectral density is relatively small in the

northern frontal zone ($40^\circ\text{N} \sim 50^\circ\text{N}$), because the mixing ratio decreases northward. The propagation pattern (*i.e.*, phase lines) indicates similar features to those in the vorticity field, although the wavelength differs a little from that in the vorticity field.

The top panel of Fig. 8 shows 5.86-day period spectral density of Ch amounts with phase lines. The large spectral density of Ch amounts is seen in the Baiu front and around the northeastern rim of the Qinghai-Xizang Plateau. The propagation pattern shows similar features to those in the moisture field (Fig. 7). It should be noted that the "bended phase line" or "hooked-shape propagation pattern"

Fig. 7. As in Fig. 6, but for 500 mb mixing ratio (q). The isolines of density are given with $2 \times (\text{gr}/\text{kgr})^2$ day interval. The black circles present the position of the grid points S1~S7, at which the vertical phase relationship is shown in Fig. 9. The thick broken line presents the position of the vertical section of Fig. 11.

of the disturbances with 5.86-day period is commonly found in the vorticity, mixing ratio and Ch fields over the areas east of $\sim 130^\circ\text{E}$.

As noted above, the time changes of cloud distributions in the Baiu frontal zone and in $40^\circ\text{N}\sim 50^\circ\text{N}$ deeply related to the passage of the synoptic-scale period vorticity disturbances, although the cloud amounts were rather small in the northern part ($40^\circ\text{N}\sim 50^\circ\text{N}$) of the disturbances. A significant part of the cloud variations in the Baiu front is attributed to the synoptic-scale disturbances which propagate from Central Asia to the east in the upper westerly zone.

A typical example of the disturbance with ~ 6 -day period

Features of the ~ 6 -day period variations found in the present spectral analysis will be examined in individual cases. The synoptic-scale (~ 6 -day) period variations in/around the Baiu frontal cloud zone are most evident during 11~20 July 1982 (Periods 3, 4, the active shallow-type Baiu front, see Part II). As a typical example of cloud variations associated with a ~ 6 -day period disturbance, Fig. 18 (in Section 6-b) is referred. In Fig. 18, the T_{BB} (cloud top black body temperature measured from GMS-IR observation) maps at 12GMT 13, 12GMT 15, 00GMT 17 and 00GMT 19 July 1982 are presented. In 13~19 July 1982 (in the 6-day period), a large cloud zone which consisted of a few mesoscale cloud clusters, propagated slowly east/east-southeastward, as extending along a synoptic-scale trough. The propagation pattern in the vorticity, mixing ratio and Ch fields obtained from the spectral analysis coincides

well with the movement of the large cloud zone observed in Fig. 18.

Vertical structure

Figure 9 shows vertical phase relationships for vorticity (ζ) and mixing ratio (q) at the grid points S1~S7 noted in Fig. 7. The grid points S1~S4 and S5~S7 align along the W-jet and the B-jet (Fig. 3) during Periods 3 and 4, respectively. The tilt of the vertical axis of the vorticity disturbances was small over the inland of the continent. The tilt increased east/southeastward and was the largest at the grid point S7. Figure 10 shows the vertical phase difference between the 700 mb and 300 mb levels in the height fields. The positive value indicates westward tilt. Inland (Central Asia and the Mongolian Plateau), the value changed from positive into negative. On the contrary, around 120°E to the east, the baroclinic structure of the disturbance was evident (positive value), and the north-south extension of the disturbance was about 2000 km. These features indicate that the synoptic-scale period disturbances changed rapidly in their vertical structure and intensity during the movement of a short distance (3000 km) from the inland (grid point S1) to the east coast (grid point S4).

It is also pointed out that the vertical structure in the southern part (grid points S6, S7 in the Baiu front) of the baroclinic disturbance differed from that in the northern part (grid points S3, S4 in $40^\circ\text{N}\sim 50^\circ\text{N}$). Figure 11 presents the NW-SE vertical section of phase of the 5.86-day period disturbance. The vertical axis of vorticity tilted north-westward with height. The vertical phase difference

Fig. 8. Latitude-longitude diagrams of power spectral density of Ch amounts during the analysis period for 5.86-day, 3.42-day, 2.41-day and 1.00-day periods. In the diagrams of 5.86-day (upper panel) and 2.41-day (middle-lower panel) periods, phase lines are noted. The black circles labeled by S1~S7 and M1~M8 present the position of the grid points in Figs. 7 and 15, respectively. The thick line in the 5.86-day period map indicates the position of NW-SE section of Fig. 11.

in the northern part (S4) was $\sim\pi/2$, while that in the southern part (S7) was $\sim\pi$.

The phase difference between the vorticity and mixing ratio fields also changes in space. In the developing stage of the baroclinic disturbance, the maxima of mixing ratio in the lower layer are generally located $0\sim\pi/2$ in front of the vorticity maxima (panels of grid points S3, S4, S6, S7 in Fig. 9) and extend nearly upright. These features indicate upward transport of moisture and, therefore upward motion in front of the disturbance's center. In the Baiu front (S6, S7), the maxima of negative vorticity are located just above the maxima of mixing ratio. This indicates the formation of anticyclonic circulation associated with upper-level divergence in the disturbance. These features are consistent with the

fact that many tall convective clouds developed in the active Baiu front.

In the monthly mean fields (see Fig. 2 of Part II), baroclinicity was intensified around the eastern coast ($\sim 120^\circ\text{E}$) of the continent, where the structure of the Baiu frontal zone also changed into a baroclinic one (Fig. 2). It is inferred that the development of synoptic-scale disturbances around the eastern coast will be due to the intensified baroclinicity and the change of the frontal structure.

6. Features of mesoscale period disturbances

In this section, ~ 3.5 -day, ~ 2.5 -day and 1-day period mesoscale disturbances will be examined. Some readers may be suspicious of the difference between ~ 3.5 - and ~ 2.5 -day periods. The spatial distribu-

Fig. 9. Vertical phase relationship at 5.86-day period for vorticity (ζ , circles) and mixing ratio (q , triangles) at the grid points S1~S7 shown in Fig. 7. The black circles (VOR, $-VOR$) and the black triangles (q) present the vertical coherence equal to or more than 0.75, between the 700 mb and the other levels. The blank circles and the blank triangles present the coherence less than 0.75. The small circles on lines $-VOR$ present the negative vorticity maximum. The upper (S1~S4) and lower (S5~S7) panels represent features of the synoptic-scale disturbance in $40^{\circ}N \sim 50^{\circ}N$ and in the Baiu front, respectively.

Fig. 10. Vertical phase difference of the height fields between 700 mb and 300 mb at 5.86-day period. The areas of phase differences more than $30 \text{ deg } (\pi/6)$ are stippled. The blank areas present the areas of coherence less than 0.75. The black areas are mountains higher than 3000 m.

Fig. 11. Vertical sections of the phase at 5.86-day period along the broken line in Fig. 7, which was calculated as centered at 700 mb of the grid point S4. The upper and lower panels are for vorticity (ζ) and mixing ratio (q), respectively. The dotted line in the upper panel indicates the phase of mixing ratio relative to that of vorticity.

tions of spectral density at both periods, however, exhibit obviously different patterns. For this reason, they will be recognized as disturbances with different characteristics.

a. 3.42-day period

Figure 12 shows the spatial distribution of spectral density and phase lines for a 3.42-day period for the 300 mb and 700 mb vorticity fields. At 300 mb, two zones of high spectral density with ~ 1000 km north-south width are found. One extends along the upper westerly jet ($40^\circ\text{N}\sim 50^\circ\text{N}$) over Central Asia and then extends east-northeastward along the 50°N latitude circle. The other extends along the Baiu front from the eastern foot ($\sim 100^\circ\text{E}$) of the Qinghai-Xizang Plateau to Japan ($\sim 140^\circ\text{E}$). The magnitude of spectral density reaches a maximum around 120°E to 140°E in both zones. The phase lines around 100°E indicate that the path of the mesoscale disturbances in the upper westerly jet branches into two paths of east-northeastward and southeastward directions. The southern path intersects with the Baiu front at $\sim 110^\circ\text{E}$; that is, the disturbances propagated from Central Asia into the

Baiu front.

At 700 mb, two zones of high spectral density extend from $\sim 110^\circ\text{E}$ to the east in the nearly same latitude zones as those at 300 mb. The magnitude of spectral density in both zones is smaller than in the upper layer. Especially around the eastern foot ($\sim 100^\circ\text{E}$) of the Qinghai-Xizang Plateau, a high-density area is not found. This indicates that the Baiu frontal disturbances with a ~ 3.5 -day period began to develop in the lower layer at $\sim 110^\circ\text{E}$ where the upper-level disturbances in the westerly zone approached from the northwest to the Baiu front.

In the Baiu frontal zone, the phase speed was extremely small and the eastward propagation of the disturbances was limited to the range of one wavelength at most. The wavelength of the disturbances was $2000\sim 2500$ km and differed a little between the lower and the upper layers in the Baiu front.

The second panel of Fig. 8 shows spatial distributions of spectral density of Ch amounts for the 3.42-day period. A large spectral density is seen in the Baiu frontal zone between 125°E and 155°E . However, phase lines can not be given for Ch amounts; that is, the propagation of the disturbances with

Fig. 12. As in Fig. 6, but for 3.42-day period. The isolines of density are given with $20 \times 10 \times (10^{-6}/\text{sec})^2$ day intervals.

~ 3.5 -day period in the Ch field was not evident. These features indicate that the ~ 3.5 -day period disturbances were too complicated to analyze a realistic structure in terms of spectral analysis only.

Typical examples of ~ 3.5 -day period disturbances

For a more complete understanding of the results of spectral analysis, the analysis made in Part II of this study should be referred to. As typical examples of the disturbances of ~ 3.5 -day period, features of the disturbances in Period 5 (21~25 July 1982, the active-deep Baiu front) are examined, for the following reasons: the large-scale situation in Period 5 is illustrated in the lower panel of Fig. 3. In $110^\circ\text{E} \sim 150^\circ\text{E}$, the northern ($\sim 45^\circ\text{N}$) and the southern ($\sim 35^\circ\text{N}$) zones of high spectral density of 700 mb vorticity at ~ 3.5 -day period (Fig. 12) agreed with the HW-jet and the B-jet shown in Fig. 3. The

magnitude of spectral density was small in the area between the two zones (Fig. 12). These two zones of high spectral density coincided approximately with the paths of the disturbances during Period 5 (Fig. 10 of Part II). The results of spectral analysis of Ch amounts at 3.42-day period also exhibited large spectral density along the HW-jet and the B-jet.

The typical examples of the disturbances of ~ 3.5 -day period are seen on the successive T_{BB} maps in Fig. 13. On these maps, the vorticity maxima at 700 mb and 300 mb are also presented. The mesoscale disturbances noted by α , β and γ in Fig. 13 moved slowly, accompanying respective mesoscale cloud clusters. The vorticity disturbances developed and then decayed in a few days, propagating from $\sim 120^\circ\text{E}$ to $\sim 140^\circ\text{E}$ in the Baiu front. In the Baiu front east of $\sim 120^\circ\text{E}$, the vorticity maxima (ζ_{max}) of the disturbances are seen at the both 700 mb (pre-

Fig. 13. T_{BB} latitude-longitude diagrams showing features of the active-deep Baiu front during the 3-day period from 12GMT 22 July to 12GMT 25 July. The isotherm interval is 10°C . The symbols $\blacktriangledown$ and $\blacktriangle$ represent the position of the vorticity maximum $\zeta_{\max}$ at 300 mb and 700 mb, respectively.

sented by $\blacktriangle$) and 300 mb ($\blacktriangledown$) levels. It is an important fact that the phase relationship of $\blacktriangle$ to $\blacktriangledown$ changed with time. The horizontal gradient of T_{BB} in the mesoscale cloud clusters was very strong at 12GMT, 23 July. The strong gradient of T_{BB} is a characteristic of the clusters in the developing stage. At that time, $\blacktriangle$ ($\zeta_{\max}$ at 700 mb) in each cluster was located to southeast of $\blacktriangledown$ ($\zeta_{\max}$ at 300 mb). It is emphasized that the vertical axis of the vorticity maximum tilts northwestward with height only

in the developing stage of the associated mesoscale cloud clusters.

In short, typical disturbances of ~ 3.5 -day period were seen in the active-deep Baiu front. In the active-deep Baiu front, the mesoscale cloud clusters tended to develop when the low-level disturbances coupled with the upper-level ones.

b. 2.41-day period

Spatial variations

Figure 14 shows the spatial distribution of spectral density and phase lines for a 2.41-day period for the 300 mb and 700 mb vorticity fields.

In $40^{\circ}\text{N}\sim 50^{\circ}\text{N}$, a high-density zone at 700 mb extends from the Mongolian Plateau ($\sim 100^{\circ}\text{E}$) to the eastern coast ($\sim 130^{\circ}\text{E}$) of the continent. At 300 mb, a high-density zone extends from Central Asia to the eastern coast of the continent. The magnitude of the density at 300 mb reaches a maximum in $100^{\circ}\text{E}\sim 130^{\circ}\text{E}$, and it is much larger than that at 700 mb. These features show that the ~ 2.5 -day period disturbances with north-south extension of ~ 1000 km that propagated from Central Asia in the W-jet began to develop through the whole troposphere at $\sim 100^{\circ}\text{E}$ and became the disturbances of a deep structure. Then the deep disturbances began to decay at $\sim 130^{\circ}\text{E}$.

In the Baiu frontal zone ($30^{\circ}\text{N}\sim 40^{\circ}\text{N}$), a high spectral density zone of ~ 1000 km north-south width is seen in $120^{\circ}\text{E}\sim 150^{\circ}\text{E}$ at 700 mb (Fig. 14). In this zone, the magnitude of spectral density is very small at 500 mb and is largest at 850 mb (figures for 500 mb and 850 mb are not shown). At 300 mb, as noted above, a zone of high spectral density extends in $40^{\circ}\text{N}\sim 50^{\circ}\text{N}$. The zone spreads to the south and covers the Baiu frontal zone east of $\sim 110^{\circ}\text{E}$. However, the magnitude of density at 300 mb is very small in the Baiu front and the wavelength at 300 mb shown by the phase lines differs significantly from that in the lower layer. These features indicate that the Baiu frontal mesoscale disturbances of ~ 2.5 -day period with ~ 1000 km north-south extension developed only in the lower layer of the Baiu frontal zone east of $\sim 120^{\circ}\text{E}$.

It is obvious that the two kinds of mesoscale disturbances with ~ 2.5 -day period developed in the Baiu front and in the $40^{\circ}\text{N}\sim 50^{\circ}\text{N}$ latitude zone, respectively. The mesoscale deep disturbances reached a maximum in $100^{\circ}\text{E}\sim 130^{\circ}\text{E}/40^{\circ}\text{N}\sim 50^{\circ}\text{N}$, while the mesoscale shallow disturbances begin to develop around 120°E in the Baiu front. However the dynamical implication for the relationship between the two kinds of the disturbances is not known.

Phase-speed and wavelength

Next, the wavelength/phase-speed of the ~ 2.5 -day period disturbances will be examined (Fig. 14). In the Baiu front, features of the wavelength/phase-

Fig. 14. As in Fig. 6, but for 2.41-day period. The isolines of density are given with $20 \times 10 \times (10^{-6}/\text{sec})^2$ day intervals. The black circles present the position of the grid points M1~M8 in Fig. 15.

speed in the lower layer significantly differ from those in the upper layer, except over Japan. Over Japan, where the magnitude of spectral density reaches a maximum in the lower layer, the phase speed of $\sim 10^\circ$ long/day (wavelength, ~ 2000 km) in the lower layer is approximately equal to that in the upper layer. In $40^\circ\text{N} \sim 50^\circ\text{N}$, the phase speed of $\sim 10^\circ$ long/day is nearly equal throughout the troposphere.

Figure 15 shows spatial distributions of 2.41-day period spectral density of mixing ratio at 700 mb. A zone of high spectral density is also found in the Baiu front. The wavelength/phase-speed for mixing ratio coincides approximately with that for vorticity in the lower troposphere. The results of spectral analysis of Ch amounts for the 2.41-day period (the third panel of Fig. 8) also showed nearly the same wavelength and phase-speed. These features

indicate that the development of the shallow disturbances with ~ 2.5 -day period in the Baiu front was closely related to the development of mesoscale cloud clusters. The upper-level high spectral density of 2.41-day period in the Baiu front over Japan is accounted for by the variations of negative vorticity due to outflow from the developing cloud clusters, as shown in Figs. 16 and 17.

Relationship between mesoscale (~ 2.5 -day period) disturbances in the Baiu front and in $40^\circ\text{N} \sim 50^\circ\text{N}$

The low-level disturbances in the Baiu front and in $40^\circ\text{N} \sim 50^\circ\text{N}$ (the northern frontal zone, see Part II) developed nearly in phase, that is, the phase lines for 700 mb vorticity extend nearly north-southward in $30^\circ\text{N} \sim 50^\circ\text{N}$ (Fig. 14). This indicates that the Baiu frontal shallow disturbances developed in connection with the northern frontal deep disturbances.

Fig. 15. As in Fig. 6, but for 700mb mixing ratio (q) at 2.41-day period. The isolines of density are given with $1 \times (\text{gr}/\text{kgr})^2$ day intervals. The black circles present the position of the grid points M1~M8, at which vertical phase relationship is shown in Fig. 16.

To identify features of the disturbances of ~ 2.5 -day period, some typical cases should be presented. Typical examples of the ~ 2.5 -day period disturbances are seen in 11~20 July 1982 (Periods 3 and 4, the periods of the active-shallow Baiu front), because the zones of high spectral density of 700 mb vorticity at 2.41-day period (Fig. 14) coincided with the paths of the disturbances during 11~20 July (see Fig. 7 of Part II). Figure 18 shows T_{BB} maps at 12GMT 13, 12GMT 15, 00GMT 17 and 00GMT 19 July 1982. The positions of the shallow disturbances in the Baiu frontal zone (indicated by B) and the deep disturbances in the northern frontal zone (indicated by N) are also given in Fig. 18. These disturbances aligned with $\sim 2000\text{km}$ intervals and were accompanied by mesoscale cloud clusters. It is known from Fig. 18 that the shallow disturbances (Bs) in the Baiu front and the deep disturbances (Ns) in the W-jet stream (the northern frontal zone) developed nearly in phase. That is, the southern and northern mesoscale disturbances were located nearly in the same longitudes in pairs.

Vertical structure of the disturbances in the Baiu front

Figure 16 shows vertical phase differences at the grid points M1~M8 (see Fig. 15 for grid points). The vertical structure of the disturbances over Japan is examined, where the magnitude of spectral density and coherences between levels are great. In the Baiu front (lower panels of Fig. 16), the coherences between 700 mb and other levels increase eastward (from the grid point M5 to M8) and reach a maximum around 140°E (M8). The presence of the 2.41-day period disturbance is statistically most

evident over Japan. The vertical phase line (vertical axis of the disturbance) of vorticity exhibits a discontinuity in the middle layer through the grid point M5 to M8. At 140°E (M8), the axis of vorticity tilts eastward with height in the lower troposphere. The axis of mixing ratio also tilts eastward with height, and it locates just in front of the axis of positive vorticity. In the upper layer above the axis of mixing ratio, the negative vorticity is maximized. These features of the ~ 2.5 -day period disturbances and associated moisture fields are similar to those of a medium-scale ($\sim 1000\text{ km}$) disturbance developed in the Baiu front over Japan, which was analyzed by Ninomiya and Akiyama (1971).

The coherences between various levels in the vorticity and mixing ratio fields indicate high values at the grid point M8. A three-dimensional structure of the 2.41-day period disturbances centered at M8 is presented in Fig. 17. Judging from the values of the coherences between levels and between grid points around M8, the north-south extension of the disturbance is about 1000 km (about 5 grids). The axis of vorticity (circles) tilts eastward with height in the southern part of the disturbance and westward in the northern part. In the lower layer, the phase of vorticity in the northern part precedes that in the southern part.

The horizontal phase lines of mixing ratio (triangles) at each level are approximately directed north-south and they extend upward, tilting eastward with height. The horizontal axis of negative vorticity (small circles) is found above the axis of mixing ratio. In the southern part of the disturbance in the lower layer, moisture is maximized in front of ζ_{max} , while in the northern part moisture is maximized be-

Fig. 16. As in Fig. 9, but for 2.41-day period at the grid points M1~M8 shown in Fig. 15. The upper (M1~M4) and lower (M5~M8) panels represent features of the mesoscale disturbances in $40^{\circ}\text{N}\sim 50^{\circ}\text{N}$ and in the Baiu front, respectively.

hind of $\zeta_{\max}$. These differences in circulation and the moisture field between the southern and northern parts of the disturbance may be related to the difference in the cloud/rain features between the southern and northern parts of the Baiu frontal mesoscale cloud cluster over Japan (Akiyama, 1984a, b).

Vertical structure of the disturbances in $40^{\circ}\text{N}\sim 50^{\circ}\text{N}$

The 2.41-day period disturbances in $40^{\circ}\text{N}\sim 50^{\circ}\text{N}$ show the vertical structure of a baroclinic wave, as the axis of vorticity tilts westward with height throughout most of the troposphere (upper panels of Fig. 16). The vertical axis of the geopotential height field also tilts westward with height (figures are not shown). However, the tilt changes from longitude to longitude. The tilt is large between $110^{\circ}\text{E}\sim 130^{\circ}\text{E}$ (M2, M3) where the magnitude of spectral density is also large (Fig. 14), while the tilt at the grid point M4 ($\sim 135^{\circ}\text{E}$) is small and the magnitude of spectral density is also small. The baroclinic disturbance began to change its structure into a barotropic one at $\sim 135^{\circ}\text{E}$.

The magnitude of spectral density of mixing ratio in $40^{\circ}\text{N}\sim 50^{\circ}\text{N}$ was small throughout the analysis domain, as compared with that in the Baiu

front (Fig. 15). The vertical coherence is also small throughout the troposphere, except in the lower layer of M3 and M4. In $40^{\circ}\text{N}\sim 50^{\circ}\text{N}$, the spectral density of Ch amounts for a 2.41-day period (the third panel of Fig. 8) is significantly small, except at $\sim 130^{\circ}\text{E}$ (M3 and M4), where the vertical axis of mixing ratio is located $\sim \pi/2$ in front of $\zeta_{\max}$. These features indicate that mesoscale cloud clusters developed in $120^{\circ}\text{E}\sim 130^{\circ}\text{E}$, in association with the baroclinic disturbances, and then the clusters began to decay around 135°E where the disturbances began to change into barotropic ones.

Relationship between mesoscale (~ 2.5 -day period) and synoptic-scale disturbances

In $110^{\circ}\text{E}\sim 150^{\circ}\text{E}$, the ~ 6 -day period disturbances developed in a region of ~ 2000 km north-south width ($30^{\circ}\text{N}\sim 50^{\circ}\text{N}$, see Fig. 6). In the same longitudes, the ~ 2.5 -day period disturbances with ~ 1000 km north-south width were also formed in $30^{\circ}\text{N}\sim 40^{\circ}\text{N}$ and in $40^{\circ}\text{N}\sim 50^{\circ}\text{N}$, separately (Fig. 14). These indicate the relationship between the ~ 2.5 -day period and ~ 6 -day period disturbances. We should identify the relationship between them by inspecting typical cases. Typical disturbances of ~ 2.5 -day and 6-day periods were seen during 11~20

THE THREE-DIMENSIONAL STRUCTURE OF MESOSCALE SHALLOW FRONTAL DISTURBANCES

Fig. 17. The three-dimensional structure of the 2.41-day period shallow disturbance in the Baiu front, presented by the phase of vorticity (ζ , circles) and mixing ratio (q , triangles). The phase was calculated as centered at 700 mb vorticity of the grid point M8. The lateral stripes represent the phase difference between vorticity and mixing ratio for each level. The small circles at 100 mb, 200 mb and 300 mb present the negative vorticity maximum ($-VOR$).

July 1982 (Periods 3 and 4, the active-shallow Baiu front). Therefore, Fig. 18 is referred to again. The vorticity maxima at 700 mb and 300 mb are noted on the T_{BB} maps of Fig. 18.

In 13~19 July 1982, a large cloud zone extended along a synoptic-scale trough slowly propagated east/east-southeastward (compare the position of the cloud zone on each panel in Fig. 18). In 13~19 July, some mesoscale deep disturbances (noted by N) with the wavelength of ~ 2000 km aligned in the northern part of the synoptic-scale disturbance, and some mesoscale shallow disturbances (noted by B) with the wavelength of ~ 2000 km aligned in the southern part (the Baiu front) of the synoptic-scale disturbance. The southern and northern mesoscale

Fig. 18. As in Fig. 13, but for the active-shallow Baiu front during the 6-day period (12GMT 13 to 00GMT 19, July 1982). $\zeta_{\max}$ at 700 mb in the Baiu front and in the northern front is noted by B and N, respectively.

disturbances were located nearly in the same longitudes in pairs. It is noted that these northern deep and southern shallow mesoscale disturbances developed as subsystems of one synoptic-scale disturbance. In other words, a synoptic-scale disturbance was composed of some mesoscale disturbances of two kinds. The synoptic-scale and the mesoscale deep disturbances, which come from Central Asia to the eastern coast of the continent in the upper westerly zone (W-jet), provide conditions favorable for the development of the mesoscale shallow disturbances in the active-shallow Baiu front, through

Fig. 19. As in Fig. 6, but for 1.00-day period at 500 mb (upper panel) and 700 mb (lower panel). The isolines of density are given with $10 \times 10 \times (10^{-6}/\text{sec})^2$ day intervals.

intensifying baroclinicity and convective instability in the frontal zone.

c. One-day period

Spatial variations

Figure 19 shows spatial distributions of spectral density for a 1.00-day period for the 700 mb and 500 mb vorticity fields. In Fig. 19, some small areas (500 km~1000 km) of high density of 700 mb vorticity are found in the Baiu front and overland, especially around the Quinghai-Xizang and the Mongolian Plateaus. At 500 mb, which nearly coincides with the ground surface of the Plateaus, some small areas of high spectral density are found on the Plateaus. At 300 mb (figure is not shown), which nearly coincides with the outflow level of mesoscale Cb clusters, some small areas of high spectral density are found approximately above the areas of high

spectral density in the lower troposphere. Around the Plateaus, the spectral density of vorticity for a 1.00-day period is much larger than that for 2.41-day and 3.42-day periods. Part I of this study showed that the mesoscale convective cloud clusters with ~1-day period developed in geographically fixed areas over the continent. Part II also showed the presence of many weak vortices around the Plateaus, which developed in association with the mesoscale cloud clusters.

Relationship between one-day period disturbances and other disturbances

Although many mesoscale shallow-weak vortices were generated with a 1-day period around the Quinghai-Xizang Plateau, only some of them in the Baiu frontal zone selectively or sporadically developed with an interval of a few days, propagat-

ing eastward along the frontal zone. They developed into long-lived mesoscale disturbances under the influence of synoptic-scale (~ 6 -day period) and mesoscale ($2\sim 3$ -day period) disturbances which propagated from Central Asia to the eastern coast of the continent in the upper westerly zone (in $40^\circ\text{N}\sim 50^\circ\text{N}$).

Under the large-scale situation as in Periods 3 and 4 (*i.e.*, the active-shallow Baiu front), the mesoscale vortices developed into long-lived mesoscale shallow disturbances in the Baiu front, making pairs with the northern mesoscale deep disturbances, in a synoptic-scale trough. While, under the large-scale situation as in Period 5 (*i.e.*, the active-deep Baiu front), the mesoscale vortices became the long-lived mesoscale deep disturbances in the Baiu front, through coupling with the mesoscale upper-level disturbances approached from the northwest.

7. Summary and remaining problems

The main purpose of this study is to clarify space-time variations of the Baiu frontal activity (cloud distributions, associated disturbances, frontal structure) during the one-month period of July 1982. Attention is focused on differences in the active and the inactive phases of the Baiu front and regional differences in frontal activity between the eastern part (Northwest Pacific) and the western part (China continent) of the Baiu front. In Part I of this study (Akiyama, 1989), the large-scale features in the vicinity of the front and the space-time variations of cloud distributions have been described. The results revealed that the features of cloud variations in the frontal zone changed greatly from the west toward the east, in accordance with the change of large-scale frontal situations. In Part II, the vertical structure of the Baiu frontal zone and the behavior of the disturbances related to the Baiu frontal activity during the six 5-day subperiods were studied, mainly by analyzing the vorticity fields. In Part III, the space-time scale and the structure of the disturbances are studied by spectral analysis on the vorticity (ζ), mixing ratio (q), and height (Z) fields. Special attention is paid to the interaction between the disturbances in the Baiu frontal zone and in the upper westerly jet.

The results of Part III are summarized as follows:

- (1) From spectral analysis of the vorticity fields, four prominent periods, a synoptic-scale (~ 6 -day) and three mesoscale (one-day, ~ 2.5 -day and ~ 3.5 -day) periods, were found in and around the Baiu frontal zone. These periods coincided well with the prominent periods in the time variations of high-cloud (Ch) amounts obtained in Part I.
- (2) The synoptic-scale period disturbances propagated from Central Asia in the upper westerly zone (along the W-jet) to the east, whilst changing their structure. They developed into baroclinic distur-

bances around the eastern coast ($\sim 120^\circ\text{E}$). At that time, the Baiu frontal large cloud zone was formed along the disturbance's trough.

- (3) The mesoscale shallow-weak disturbances (vortices) of one-day period developed in the Baiu front over the continent. Some of them developed into the long-lived mesoscale disturbances, propagating east along the B-jet (the low-level Baiu jet), under the influence of the upper-level disturbances with $2\sim 3$ -day and/or ~ 6 -day periods, which propagated from Central Asia in the W-jet.

- (4) In the active-shallow Baiu front, the mesoscale shallow disturbances of one-day period along the B-jet began to develop into the shallow disturbances of ~ 2.5 -day period around 120°E and then reached the maximum intensity around Japan ($\sim 140^\circ\text{E}$). In this stage, the vertical axis of vorticity of the disturbances tilted eastward with height in the southern part, but westward in the northern part. In the southern part, the mixing ratio reached the maximum in front of the vorticity maximum. In the upper layer above the maximum of mixing ratio, anticyclonic circulation was maximized.

- (5) During the periods of the active-shallow Baiu front, the mesoscale (~ 2.5 -day period) shallow disturbances in the Baiu front ($30^\circ\text{N}\sim 40^\circ\text{N}$) and the mesoscale (~ 2.5 -day period) deep disturbances along the W-jet were located nearly at the same longitude in pairs. These two kinds of mesoscale disturbances developed in a synoptic-scale disturbance as its subsystems and composed multi-scale structures of a Baiu frontal large cloud system of synoptic-scale.

- (6) In the active-deep Baiu front, the mesoscale shallow disturbances of one-day period along the B-jet over the continent developed into the mesoscale deep disturbances of ~ 3.5 -day period around the east coast ($\sim 120^\circ\text{E}$), coupling with the upper-level mesoscale disturbances propagated from Central Asia along the W-jet. The mesoscale cloud clusters developed in the Baiu front, when the center of the low-level vorticity disturbances was located southeast of that of the upper-level vorticity disturbances.

- (7) Although the period, structure and evolution process of those mesoscale-period disturbances differed from each other in accordance with the large-scale and/or synoptic-scale situations of the Baiu front, they were accompanied by respective mesoscale cloud systems and carried the mesoscale-period cloud variations in the Baiu frontal zone.

Characteristics of the vorticity disturbances revealed in Part II and III are summarized in Table 2. It is stressed that the features of the synoptic- and meso-scale vorticity disturbances in the Baiu front changed greatly from the west (over the continent) toward the east (over Japan to the northwest Pacific).

Table 2. Characteristics of the vorticity disturbances in/around the Baiu front.

scale	period	depth	vertical axis	predominant region	cyclonic circulation
synoptic	~6-day	deep	westward-tilt	120°E~150°E/ 50°N~30°N	intense in the upper layer
meso	~3.5-day	deep	westward-tilt (sometimes)	120°E~140°E in Baiu front	intense
	~2.5-day	deep	westward-tilt	100°E~130°E/ 40°N~50°N	intense in the upper layer
	~2.5-day	shallow	eastward-tilt (south side) westward-tilt (north side)	120°E~140°E in Baiu front	moderate
	1.0-day	shallow	—	90°E~110°E/ 30°N~50°N	weak
large (a low)	>~6-day	(to intensify baroclinicity in/around the Baiu frontal zone)			

Although many interesting features about the space-time variations of the clouds and/or the disturbances in and around the Baiu front have been found in the present study, the following problems remained to be solved in the future:

(1) The high-cloud amounts in the Baiu front over the continent were larger than those over Japan, while the synoptic-scale and 2~3-day period mesoscale disturbances usually developed around the coastal region of the continent to Japan. The role of convection in the development of these disturbances should be examined.

(2) The relationship between the development of these disturbances around the eastern coast and a quasi-stationary trough (Baiu trough, *e.g.* see Saito, 1985; Ninomiya and Muraki, 1986) was not discussed in this study.

(3) In this study, the Baiu frontal activity was examined based on mainly statistical procedure (*i.e.*, spectral analysis). Further case studies on the evolution of these disturbances and associated cloud systems will be necessary.

(4) The coupling process of the upper-level disturbances with the low-level ones, as seen for the ~3.5-day period disturbances in the active-deep Baiu front, and the interaction between the mesoscale disturbances in the active-shallow Baiu front and in the northern front, as seen for the ~2.5-day period disturbances, were not clarified fully in this study.

(5) In this study, the vertical structures of the disturbances in the height and temperature fields were not fully discussed, because their vertical coherences indicated small values. A study on the height and temperature fields will be necessary.

As for these problems, some case studies have been made (*e.g.*, see Yoshizumi, 1977, 1978; Chen and Dell'Osso, 1984; Akiyama 1984a, b; Ninomiya and Muraki, 1986; Kuo *et al.*, 1986). However,

these studies did not answer fully the aforementioned problems. For a further understanding of the Baiu frontal activity, more detailed studies will be needed.

Acknowledgments

The author wishes to express her appreciation to Dr. K. Ninomiya, JMA, for his comments on reviewing this manuscript, to Dr. K. Kato, Nagoya University, and one of the reviewers, for their useful advice. Her thanks are extended to Dr. T. Maruyama, Meteorological Research Institute, who permitted her to use his computer program for spectral analysis.

References

- Akiyama, T., 1973: The large-scale aspects of the characteristic features of the Baiu front. *Pap. Met. Geophys.*, **24**, 157–188.
- Akiyama, T., 1978: Mesoscale pulsation of convective rain in medium-scale disturbances developed in Baiu front. *J. Meteor. Soc. Japan*, **56**, 267–283.
- Akiyama, T., 1984a: A medium-scale cloud cluster in a Baiu front. Part I: Evolution process and fine structure. *J. Meteor. Soc. Japan*, **62**, 485–504.
- Akiyama, T., 1984b: A medium-scale cloud cluster in a Baiu front. Part II: Thermal and kinematic fields and heat budget. *J. Meteor. Soc. Japan*, **62**, 505–521.
- Akiyama, T., 1989: Large, synoptic and meso scale variations of the Baiu front, during July 1982. Part I Cloud features. *J. Meteor. Soc. Japan*, **67**, 57–81.
- Akiyama, T., 1990: Large, synoptic and meso scale variations of the Baiu front, during July 1982. Part II Frontal structure and disturbances. *J. Meteor. Soc. Japan*, **68**, 557–574.
- Chen, S.-J. and L. Dell'Osso, 1984: Numerical prediction of the heavy rainfall vortex over Eastern Asia monsoon region. *J. Meteor. Soc. Japan*, **62**, 730–747.

- Kato, K., 1985: On the abrupt change in the structure of the Baiu front over the China continent in late May of 1979. *J. Meteor. Soc. Japan*, **63**, 20–36.
- Kuo, Y.-H., L. Cheng and R.A. Anthes, 1986: Mesoscale analyses of the Sichuan flood catastrophe, 11–15 July 1981. *Mon. Wea. Rev.*, **114**, 1984–2003.
- Ma, K.-Y. and L.F. Bosart, 1987: A synoptic overview of a heavy rain event in Southern China. *Weather Forecast*, **2**, 89–112.
- Matsumoto, S., S. Yoshizumi and M. Takeuchi, 1970: On the structure of the Baiu front and the associated intermediate-scale disturbances in the lower atmosphere. *J. Meteor. Soc. Japan*, **48**, 479–491.
- Murakami, T. and W.-G. Huang, 1984: Orographic effects of the Tibetan Plateau on the rainfall variations over central China during the 1979 summer. *J. Meteor. Soc. Japan*, **62**, 895–909.
- Ninomiya, K. and T. Akiyama, 1971: The development of the medium-scale disturbance in the Baiu front. *J. Meteor. Soc. Japan*, **49**, Special Issue, 663–677.
- Ninomiya, K. and T. Akiyama, 1974: Band structure of mesoscale echoclusters associated with low-level jet stream. *J. Meteor. Soc. Japan*, **52**, 300–313.
- Ninomiya, K., M. Ikawa, and T. Akiyama, 1981: Long-lived medium-scale cumulonimbus cluster in Asian subtropical humid region. *J. Meteor. Soc. Japan*, **59**, 564–577.
- Ninomiya, K. and H. Muraki, 1986: Large-scale circulations over East Asia during Baiu period of 1979. *J. Meteor. Soc. Japan*, **64**, 409–429.
- Saito, N., 1985: Quasi-stationary waves in mid-latitudes and the Baiu in Japan. *J. Meteor. Soc. Japan*, **63**, 983–995.
- Tao, S.-Y. and Y.-H. Ding, 1981: Observational evidence of the influence of the Qinghai-Xizang Plateau on the occurrence of heavy rain and severe convective storms in China. *Bull. Amer. Meteor. Soc.*, **62**, 23–30.
- Yoshizumi, S., 1977: On the structure of intermediate-scale disturbances on the Baiu front. *J. Meteor. Soc. Japan*, **55**, 107–120.
- Yoshizumi, S., 1978: On an upper tropospheric disturbance of 2.5-day period around the jet stream in the Baiu frontal zone. *J. Meteor. Soc. Japan*, **56**, 243–252.

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 III : 擾乱の時空間規模と構造

秋山孝子

(気象研究所)

Part I で梅雨前線上の雲変動について記述し、大規模場の傾圧性が強化され前線南側下層の南風成分の増加している時期に、梅雨前線上の雲量も多いこと、雲量変動周期および雲クラスターの様相に地域性のあることを示した。Part II では前線帯の垂直構造と前線活動に関連した擾乱の振舞いを、主に相対渦度場で解析し、雲量の多い時期に、前線上の擾乱は大陸の東岸で発達する傾向にあることを指摘した。Part III では擾乱の時空間 scale・垂直構造、scale の異なる擾乱間の相互関係をスペクトル解析の結果にもとずいて調べ、下記の様相を見出した：

(1) 渦度場のスペクトル解析から、梅雨前線とその近傍で、雲量の場合と同様に、総観規模 (~6 日) 及び三つの中規模 (~3.5、~2.5、1.0 日) 周期が見出された。これらの周期の擾乱は相互作用を及ぼしつつ、複雑な発達過程を示している。

(2) チベット高原周辺の前線上 (30°N~40°N) に、背の低い弱い低気圧性循環の擾乱が 1 日周期で数多く形成される。その内の幾つかは前線を東へ移動し、上層偏西風 jet (40°N~50°N) 内を西から移動してくる擾乱の影響下、大陸東岸 (~120°E) あたりで発達し始め、より長い周期の中規模擾乱となる。

(3) 上層 jet 内を中央アジアから移動して来る総観規模擾乱が大陸東岸で発達し、梅雨前線の雲帯がそのトラフに沿って形成される状況下では (period of the active-shallow Baiu front)、上層ジェット内 (40°N~50°N) を西から移動し大陸東岸で発達する ~2.5 日周期の背の高い擾乱があらわれる。(2) で述べた 1 日周期の擾乱はこの背の高い中規模擾乱の南に対となって発達し、梅雨前線上 (30°N~40°N) の ~2.5 日周期の背の低い擾乱となる。前線北側および前線上で発達する複数個の ~2.5 日周期中規模擾乱は、一個の総観規模擾乱の北部および南部の subsystems を構成している。

(4) 大陸東岸から日本列島にかけての梅雨前線が傾圧帯の構造を示す状況下では (period of the active-deep Baiu front)、(2) で述べた 1 日周期の擾乱は、上層 jet 内を西から移動して来る中規模擾乱と、大

陸東岸 ($\sim 120^{\circ}\text{E}$) で coupling し梅雨前線上の背の高いより長い (~ 3.5 日) 周期の中規模擾乱へと発達する。

(5) 梅雨前線上の中規模擾乱の周期 (1 日、 ~ 2.5 日、 ~ 3.5 日)・構造・発達過程は、大規模的にみた前線帯の構造の東西の違い或は時期 (period) の違いにより異なるけれども、いずれも中規模雲システムを伴っており、前線上の雲量に中規模周期の変動をもたらしている。