Large-Scale Circulations over East Asia during Baiu Period of 1979

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(Manuscript received 3 February 1986, in revised form 31 March 1986)

Abstract

Large-scale situation over East Asia during the Baiu period of 1979 was studied on the basis of 10-day averaged fields.

The development of warm ridge over the Mongol ~ Sibirsk Plateaus (Baiu ridge) and cold trough elongated from the Bering Sea cyclone to China (Baiu trough) were the major systems in Baiu season in middle ~ high latitudes. With the rapid temperature rise over the Continent and the slow temperature rise over the Pacific north of $\sim 35^{\circ}\text{N}$, the large temperature difference between the Continent and the Pacific was maintained. The circulations in the lower troposphere in the Baiu season were characterized by the northerly wind in the west side of the Baiu trough (Baiu-trough-northerly), the southerly wind over the South China Sea, low-level-jet like strong WSW wind along the northern periphery of the Pacific anticyclone, and the Indian monsoon westerly wind.

While the Meiyu front was related with a shear line between the South China Sea southerly and the Baiu-trough-northerly wind (Baiu shear line), the Baiu front was located ~ 1500 km south of the Baiu trough and associated with convergence/confluence of SW wind to the strong WSW wind zone. Another feature of interest is the difference between the structure of the Meiyu and the Baiu fronts.

The northward advance of the Pacific anticyclone and the Baiu front is the basic seasonal change. The quasi-periodic (~ 40 -day period) intraseasonal variations of the Pacific anticyclone and the Baiu front were superposed upon this seasonal change. The intraseasonal variations of the Baiu front were related to the activity of ITCZ in the South China Sea as well as the variations of the monsoon precipitation.

From the analysis, the role of the Tibetan Plateau, the Baiu-trough-northerly wind, cold advection associated with the Bering Sea cyclone over the cold northwestern Pacific in maintaining the Baiu/Meiyu front was inferred. This inference was supported by the results of prediction experiment by Nakamura, Hasegawa and Ninomiya (1985).

1. Introduction

June and July are the rain season over East Asia. A quasistationary front extends along $30 \sim 40^{\circ}\text{N}$ over China (Meiyu front) and Japan (Baiu front). A cloud/precipitation zone associated with the front extends from South China to Japan and farther to the Pacific.

Many observational studies and a few numerical simulations on the Baiu front and Baiu frontal disturbances (e.g., Akiyama, 1973, 1978, 1984; Matsumoto *et al.*, 1970, 1971; Muraki,

1985; Ninomiya, 1978, 1980, 1984; Ninomiya and Akiyama, 1971; Ninomiya and Yamazaki, 1979; Ninomiya *et al.*, 1981, 1984; Yoshizumi, 1977) have shown the following features:

(1) The Baiu front is located along the northern boundary of tropical maritime airmass. The structure of the Baiu front is different from that of the polar front, which is located around 60°N in June and July.

(2) The Baiu front is associated with the low-level-jet like strong WSW winds in 900 ~ 700 mb, large moisture gradient and thick moist

neutral (low Ri number) layer. The thermal gradient in the frontal zone is weak over the area to the west of 135°E.

(3) Medium-scale (meso- α -scale) frontal depressions develop along the Baiu front.

(4) Intense Baiu precipitation is produced by successive development of these depressions. In many cases, the precipitation system of a medium-scale depression is composed of a few meso- β -scale precipitation systems.

(5) The frontogenesis, generation of convective instability and the strong moisture convergence in the Baiu frontal zone are due to the confluence/convergence of SW flow along the northwestern periphery of the Pacific anticyclone to the zone of strong WSW wind.

The Japanese authors cited above paid attention mainly on the Baiu front and the circulations in the subtropical latitudes, without considering the situations in the middle and high latitudes.

On the one hand, several studies on the Meiyu front (e.g., Chen and Chang, 1980; Lau and Li, 1984) showed its association with the Meiyu trough (a trough in the lower troposphere extending from the Japan Sea to central China). Saito (1985) also pointed out that the Baiu front is located to the southeast of a 500 mb trough extending from the north Pacific to central China. Matsumoto (1985) analyzed the 850 mb wind field in relation to the frontal zone over East Asia in summer.

Recently several authors studied features of large-scale circulations over East Asia during the summer of 1979. Murakami and Ding (1982) described changes in wind and temperature fields over Eurasia in the early summer. An abrupt increase of 300 mb temperature and intensification of 300 mb anticyclone were seen around 5 June in association with the onset of rain season over China and Japan and ~ 15 days prior to the onset of Indian monsoon. The northward shift of 300 mb jet stream from 30 to 40°N and rapid establishment of 700 mb easterly around 25°N were observed over India. However the northward shift of the 300 mb jet stream was not seen over the eastern Tibetan Plateau.

Luo and Yanai (1983) described the oro-

graphic and thermal influences of the Tibetan Plateau upon the low-level wind field in the early summer. The areas of organized precipitations were related to the quasi-stationary Burma-India trough, Meiyu front and transverse trough extending eastward from the Plateau.

Murakami and Huang (1984) studied the nature of disturbances which brought the Meiyu rainfalls over China for 1 May $\sim$ 15 June (Period 1) and 16 June $\sim$ 31 July 1979 (Period 2). They described the birthplace and evolution process of the Period 1 and 2 cyclones.

Kato (1985) studied the abrupt change in the structure of Meiyu front over China in late May, which was characterized by decrease of temperature gradient in Meiyu front and the increase of convective instability.

Murakami, M. (1984 and 1985) described the northward advance of the convective area over the southeastern Asia, the formation of highly convective zone of Meiyu-Baiu front and the northward shift of ITCZ over the western Pacific in May $\sim$ August 1979 using IR data of the geostationary satellite. Intraseasonal variations with a ~ 40 -day period in convective activity and wind field related with active/break cycle of the Indian monsoon were also pointed out. Similar analysis was also made by Krishnamurti and Subrahmanyam (1982).

Nevertheless, the relation between the Baiu and Meiyu front, the influence of the middle and high latitude circulations on the Baiu/Meiyu front have not been fully studied yet. In the present paper, the authors study the large-scale features over East Asia for May $\sim$ August 1979 by analyzing 10-day averaged fields. We pay special attention on the following problems;

(1) Comparison of the Baiu front with the Meiyu front.

(2) Large-scale circulations in the middle and high latitudes related with Baiu/Meiyu precipitations.

(3) Variation of the Pacific anticyclone in relation with that of the Baiu front.

(4) Seasonal change in the large-scale fields associated with the onset and withdrawal of the Baiu/Meiyu season.

The following data are used in the present study:

- (1) Data of northern hemisphere objective analysis of JMA at 381 km grid points.
- (2) Precipitation data at surface stations.
- (3) Amount of high-cloud (higher than 400 mb level) estimated from IR observation from GMS (Geostationary Meteorological Satellite).

2. Baiu and Meiyu precipitation in 1979

Fig. 1 presents the time-series of daily precipitation averaged over each of 9 areas in the map on the upper-left part of Fig. 1. Over Japan, data on the stations indicated by blacked circle were used to calculate the area-averaged precipitation. The data on China were obtained from Murakami and Huang (1984).

Precipitation over Japan

Prior to the Baiu period, a few peaks of intense precipitation occurred in 1 ~ 15 May over $27.5 \sim 37.5^\circ\text{N}$ zone. Synoptic analysis indicated that these precipitations were associated with synoptic-scale cyclones and not the

Baiu precipitation. Alternate spells of fine weather and weak precipitation were seen in 15 ~ 30 May over $27.5 \sim 37.5^\circ\text{N}$ zone.

The Baiu precipitation in area JW_{25} began around 20 May while that in the northern areas around 5 June. The precipitation was specially intense over southwestern Japan (JW_{30} and JW_{35}) for 15 June ~ 20 July. The peak value of area-averaged precipitation reached to ~ 70 mm/day. The Baiu precipitation in JW_{25} and the northern zones ended around 20 June and 20 July respectively. No significant break of rain season, such as the Indian monsoon break, was seen over southwestern Japan.

Precipitation over China

The precipitation in C_{25} and C_{30} continued throughout for May ~ July period while that in C_{35} was seen for 15 June ~ 20 July. Murakami and Huang (1984) defined the onset of Meiyu in C_{35} on 16 June. After the onset, no significant break of monsoon rains occurred.

Fig. 1 The time-series of daily precipitation averaged over each of 9 areas indicated in the top-left map for May – July 1979. The blacked circles indicate the observation stations. The data on China were obtained from Murakami and Huang (1984).

Precipitation over India

The monsoon onset on India occurred around 15 June. The peak of the monsoon precipitation was seen in 20 ~ 30 June. July was a break period of monsoon over almost all part of India. The second eminent precipitation peak appeared around 1 August (Luo and Yanai, 1983; Murakami, M., 1985). The Meiyu and Baiyu precipitation were still intense in 5 ~ 20 July, which was the break period of Indian monsoon.

Subdivision of the analyzed period

On the basis of the distribution and the amount of the precipitation over Japan and China, the analyzed period was subdivided into the four period as indicated in Table 1.

In the following sections, we describe the characteristics of the large-scale features in these subperiods by presenting the 10-day averaged fields of various meteorological elements.

Table 1 Sub-periods of the Baiu season in 1979.

Sub-Period	Baiu/Meiyu	Indian Monsoon
May I (1-10)	Pre-Baiu	Pre-Onset
May II (11-20)	—	
May III (21-31)	Early Baiu	
Jun I (1-10)	—	Onset
Jun II (11-20)	peak Baiu	
Jun III (21-30)	—	Peak Monsoon
Jun I (1-10)	—	
Jul II (11-20)	—	Break Monsoon
Jul III (21-31)	Post-Baiu	
Aug I (1-10)	—	Second Peak

3. Characteristics of height field

Fig. 2 shows 10-day averaged 850 mb height (Z_{850}) and the high-cloud amount (C_H ; estimated only over sea areas) for May I, Jun I, Jun III and Jul III. Fig. 3 presents 10-day averaged 500 mb height (Z_{500}) and the time-variance of Z_{850} in

Fig. 2 The 10-day averaged 850 mb height (Z_{850}) and the high-cloud amount (C_H : estimated only over sea areas, dashed lines) for May I, Jun I, Jun III and Jul III, 1979. Contours of the topography of 1500, 3000 and 5000 m are shown in the maps.

Fig. 3 The 10-day averaged 500 mb height (Z_{500}) and the time-variance of Z_{850} in 10-day period ($\sigma^2 Z_{850}$, dashed lines) for May I, Jun I, Jun III and Jul III, 1979.

10-day period ($\sigma^2 Z_{850} = 1/20 \sum (Z_{850} - \bar{Z}_{850})^2$) for May I, Jun I, Jun III and Jul III.

Pre-Baiu period

A deep trough extended from a cyclone over the Taimyr Peninsula ($\sim 90^\circ\text{N}/100^\circ\text{E}$) to central Siberia and farther to the northeastern part of China ($\sim 45^\circ\text{N}/120^\circ\text{E}$). A developed anticyclone (ridge) was located over Kazakh, U.S.S.R. ($\sim 60^\circ\text{N}/60^\circ\text{E}$). There was the zone of strong height gradient (polar frontal zone) in $40 \sim 60^\circ\text{N}$. The zone of large $\sigma^2 Z_{850}$, which corresponded to the path of the major polar frontal cyclones was also seen in $40 \sim 50^\circ\text{N}$. The zone of maximum C_H was along the south side of the zone of large $\sigma^2 Z_{850}$.

Early-Baiu period

The height field in the lower and middle troposphere changed rapidly in the transitional period between the pre- and early-Baiu. At 850 mb, there was a deep trough over the Ural

Mountains, extending from a cyclone over the Kara Sea ($\sim 70^\circ\text{N}/70^\circ\text{E}$) to the Caspian Sea ($\sim 45^\circ\text{N}/60^\circ\text{E}$).

A predominant ridge extended from the north of the Tibetan Plateau ($\sim 45^\circ\text{N}/90^\circ\text{E}$) to the Mongol and Sibirs Plateau ($\sim 70^\circ\text{N}/120^\circ\text{E}$). This ridge is called "Baiu ridge" in the present paper. There was a trough extending from a stationary cyclone over the Bearing Sea ($\sim 60^\circ\text{N}/170^\circ\text{E}$; Bering cyclone) to the China Plain ($\sim 35^\circ\text{N}/120^\circ\text{E}$). This trough is called "Baiu trough" in this paper.

The zone of large $\sigma^2 Z_{850}$ was located along the southeastern side of the 500 mb Baiu trough, and the maximum zone of C_H (Baiu frontal cloud zone) was along the south side of the zone of maximum $\sigma^2 Z_{850}$. The location of this cloud zone coincided approximately with the northwestern periphery of the Pacific anticyclone. The Baiu frontal zone was ~ 1500 km south of the Baiu trough while the Meiyu frontal

precipitation zone was close to the trough. The aforementioned spatial relations among the Baiu trough, the zone of maximum $\sigma^2 Z_{850}$, the cloud zone and the Pacific anticyclone were seen throughout the early- and peak-period of Baiu.

The southern maximum zone of C_H (ITCZ cloud zone) was seen along the southwestern periphery ($\sim 10^\circ\text{N}$) of the Pacific anticyclone.

Peak period of Baiu

In this period, the zone of maximum precipitation over Japan and China was along $\sim 30^\circ\text{N}$, and the precipitation attained its maximum intensity. The monsoon precipitation over western India also reached to maximum intensity in Jun III $\sim$ Jul I.

At 850 mb, the Pacific anticyclone shifted gradually northward and its E-W axis was over $\sim 27^\circ\text{N}$ in Jun III. The Kara cyclone $\sim$ Ural trough and the Baiu ridge remained unchanged for June. The Baiu trough attained the full extension in this period. It extended WSW-ward from the Bering cyclone to the eastern foot of the Tibetan Plateau ($\sim 35^\circ\text{N}/105^\circ\text{E}$) via the Okhotsk Sea* and the northeastern part of China. Strong height gradient was seen between the Baiu trough and the Pacific anticyclone in the area east of 140°E .

Jun III and Jul I were the peak period of the Indian monsoon. There was a large low-pressure area over India and the strong height gradient (*i.e.*, zone of strong westerly wind) was over India in $\sim 20^\circ\text{N}$. The cloud of ITCZ, which was along the southwestern periphery of the Pacific anticyclone, increased significantly in this period.

At 500 mb, the Baiu ridge indicated the

Fig. 4 The longitude-time section of 10-day averaged 500 mb height (Z_{500}) at 50 and 40°N .

maximum extension toward the high latitudes. Although the height gradient in the polar region decreased significantly in this period, the large height gradient in $\sim 40^\circ\text{N}/130 \sim 170^\circ\text{E}$ were sustained between the Baiu trough and the Pacific anticyclone.

Post Baiu period

The large-scale height field over East Asia changed rapidly in the transitional period between the Baiu period and the mid-summer. The height gradient in the lower and the middle troposphere weakened rapidly in Jul II and III. The Ural trough retired poleward. In association with the decay of the Bering cyclone and the Baiu trough, a zonal height pattern with very weak height gradient was established over the East Asia and the north Pacific. The E-W axis

* The development of anticyclone over the Okhotsk Sea (Okhotsk anticyclone) has been thought to be one of the factors to maintain the Baiu front, because the NE wind along the SE hem of it advects cold air toward the Baiu front (Takahashi, 1969). However, the Okhotsk anticyclone was not seen on the 10-day averaged 850 mb height field. Since, usually the Okhotsk anticyclone appeared in the lower troposphere, and moved out within a few or several days (Suginaka, 1965), it is not necessarily recognized on the 10-day averaged 850 mb height map, except the case of unusual long persistence (Ninomiya and Mizuno, 1985).

of the Pacific anticyclone was along $\sim 30^\circ\text{N}$. The zone of maximum cloud and precipitation shifted over $\sim 40^\circ\text{N}$, and the amount of cloud and rainfall decreased.

Variation of the Baiu trough and ridge

The longitude-time sections of 10-day averaged 500 mb height, 850 mb height and that of $\sigma^2 Z_{850}$ are presented in Figs. 4, 5 and 6 respectively.

The 500 mb Baiu ridge was most predominant at 50°N in Jun I $\sim$ Jul II. It moved eastward from $\sim 95^\circ\text{E}$ (Jun I) to $\sim 120^\circ\text{E}$ (Jul II). The 500 mb Baiu trough was most evident at 40°N . It moved westward from $\sim 135^\circ\text{E}$ (May III) to $\sim 120^\circ\text{E}$ (Jun II) and then eastward to $\sim 145^\circ\text{E}$ (Jul II). The 850 mb Baiu trough was most evident at 50°N . Its maximum westward extension occurred in the peak period of precipitation (Jun III $\sim$ Jul I). The Baiu trough disappeared around Jul III.

The hatched areas in Fig. 6 shows the area of large $\sigma^2 Z_{850}$ exceeding 40 m^2 . It moved westward from $\sim 160^\circ\text{E}$ (May II) to $\sim 130^\circ\text{E}$ (Jun III) and then rapidly eastward to $\sim 180^\circ\text{E}$ (Jul III). The northeastward shift of the area of maximum cyclone activity around 40°N was deeply related with the seasonal variation of the Baiu trough.

Another conspicuous feature seen in the longitude-time section of Z_{850} at 40°N (Fig. 5, bottom) was the quasi-periodic variation in the height field with ~ 40 -day period. This intra-seasonal variation will be examined in Section 7.

4. Characteristics of wind field.

The 10-day averaged wind field at 850, 700 and 300 mb for May I, Jun I, Jun III and Jul III are presented in Figs. 7, 8 and 9.

Pre-Baiu period

The anticyclonic circulation over Kazakh, U.S.S.R. ($\sim 60^\circ\text{N}/60^\circ\text{E}$) and the cyclonic circulation over Siberia were the major circulation systems in the middle $\sim$ high latitudes. The confluence of the polar and subtropical jet streams to the east of the Siberia trough formed the strong wind zone over the Pacific.

The "transverse trough", *i.e.*, the shear line between the easterly wind in the north side and

Fig. 5 The longitude-time section of 10-day averaged 850 mb height (Z_{850}) at 50°N and 40°N .

Fig. 6 The longitude-time section of time-variance of Z_{850} in 10-day period ($\sigma^2 Z_{850}$) at 40°N .

Fig. 7 The 10-day averaged 850 mb wind velocity (V_{850}) for May I, Jun I, Jun III and Jul III, 1979.

the westerly wind in the south side, extending eastward from the eastern foot of the Tibetan Plateau (Luo and Yanai, 1983) was seen in the pre-Baiu season. The zone of strong 700 mb wind along the south side of the Tibetan Plateau extending eastward to the strong wind zone over the Pacific was also one of the characteristics in the pre-Baiu period.

Early Baiu period

The wind field over East Asia changed rapidly from the pre- to early-Baiu period. In the middle ~ high latitudes, the circulations of the Ural trough, the Baiu ridge and the Bering cyclone ~ Baiu trough were formed in the early Baiu period. The northerly wind in 850 ~ 700 mb between the Baiu ridge and the Baiu trough ($55 \sim 30^\circ\text{N}/105 \sim 125^\circ\text{E}$) was an important feature. This is called as Baiu-trough-northerly wind in this paper. A convergence/confluence line was formed between the Baiu-trough-northerly wind and the southerly wind from the South

China Sea. This is named as Baiu shear line in this paper. At 700 mb, the westerly wind in $25 \sim 30^\circ\text{N}$ zone weakened over Indo-China Peninsula, and the strong wind zone over India ($\sim 25^\circ\text{N}/65 \sim 95^\circ\text{E}$) were separated from that over the Pacific ($30 \sim 35^\circ\text{N}/120 \sim 180^\circ\text{E}$).

At 300 mb, a trough was formed over the western part of the Tibetan Plateau and staid there during the Baiu season. The strong anti-cyclonic circulation systems developed over India ~ Bay of Bengal and Indo-China ~ South China Sea areas.

Peak period of Baiu

With the full development of the Baiu trough, the Baiu trough north ~ northeasterly wind in 850 ~ 700 mb was intensified in the peak period of Baiu. As this strong north ~ northeastrly wind appeared along the eastern edge of high-land area (see 1500 m contour line in Fig. 7), some orographic effect was inferred.

The monsoon precipitation attained its

Fig. 8 The 10-day averaged 700 mb wind velocity (V_{700}) for May I, Jun I, Jun III and Jul III, 1979.

maximum intensity over western India in Jun III ~ Jul I. In 850 ~ 700 mb, the cyclonic circulation over the Bay of Bengal ($\sim 23^\circ\text{N}/80 \sim 95^\circ\text{E}$) and the westerly flow were intensified over India ~ south Bengal Bay ($\sim 20^\circ\text{N}/70 \sim 95^\circ\text{E}$). A trough (shear line) extended southeastward from the southeastern foot of the Tibetan Plateau to the South China Sea and farther to ITCZ along the southwestern periphery of the Pacific anticyclone. The southerly wind from the South China Sea to south ~ central China was rapidly intensified in this period. Concurrently, the Baiu shear line was significantly intensified.

The Baiu frontal zone was associated with low-level convergence caused by the confluence of the SW wind along the northwestern periphery of the Pacific anticyclone with the low-level-jet like WSW wind.

At 300 mb, the circulations of the Ural trough, the Baiu ridge and the Bering cyclone ~

Baiu trough were still predominant in the middle ~ high latitudes. The double-jet streams, in the north and south side of the anticyclonic circulation over the Baiu ridge were seen in $85 \sim 120^\circ\text{E}$. Three developed anticyclonic circulations, over India ~ Pakistan area, Indo-China area and the Pacific, aligned to the south of the subtropical jet stream.

Post Baiu period

As the Baiu trough vanished, the Baiu-trough north ~ northeasterly wind weakened rapidly. With the northward shift of the Pacific anticyclone, the southerly wind over China and southwesterly wind over Japan weakened too. At 300 mb, the anticyclonic circulations were predominant over 30°N .

5. Characteristics of thermal field

Fig. 10 shows the 10-day averaged 850 mb temperature (T_{850}) for May I, Jun I, Jun III and

Fig. 9 The 10-day averaged 300 mb wind velocity (V_{300}) for May I, Jun I, Jun III and Jul III, 1979.

Jul III. Fig. 11 presents the 10-day averaged 850 mb equivalent potential temperature (θe_{850}) and the difference of θe between 700 and 850 mb ($\theta e_{700} - \theta e_{850}$) for the same periods to these in Fig. 10. The longitude-time sections of 10-day averaged 850 mb temperature for May I ~ Aug I at 50 and 40°N are presented in Fig. 12.

Pre-Baiu period

In the pre-Baiu period, the horizontal temperature gradient (∇T) was strong in the area to the north of ~30°N. In 30 ~ 60°N zone, the isotherms ran approximately parallel with the latitude circles, and the continent-ocean temperature contrast was small (Fig. 12).

The moist tropical airmass ($\theta e_{850} > 340$ K) covered the Bay of Bengal, Indo-China and the South China Sea. The areas to the north of 30°N were convectively stable ($\theta e_{700} - \theta e_{850} > 0$ K). The southern part of China (> 30°N) was the most stable area ($\theta e_{700} - \theta e_{850} > 5$ K).

Early Baiu period

The 850 mb temperature in 40 ~ 70°N over the Continent rose rapidly in May ~ June. The temperature rise was most pronounced (~12°C/month) over the high-land areas (Mongol and Sibirsk Plateau). Kato (1985) pointed out that this temperature rise was mainly due to the warming of air heated by insolation. At the same time, ∇T over the Continental part of China (20 ~ 40°N/100 ~ 120°E) decreased rapidly. The Meiyu front over China lost the characteristic feature of typical polar front with strong ∇T during the early Baiu period.

Convective stability in the lower troposphere also changed rapidly in May ~ June. The isoline of ($\theta e_{700} - \theta e_{850}$) labeled by 0 K shifted northward from ~25°N (May I) to ~50°N (Jun I) over China. The aforementioned change, *i.e.*, the decrease of ∇T and the increase of convective instability in the Meiyu precipitation zone, was one of the conspicuous features found from the

Fig. 10 The 10-day averaged 850 mb temperature (T_{850}) for May I, Jun I, Jul I and Jul III, 1979.

pre- to early-Baiu period.

On the other hand, the temperature rise was less pronounced ($4^{\circ}\text{C}/\text{month}$) over the Pacific to the north of $\sim 35^{\circ}\text{N}$. The vast cold ocean prevented the warming of air. The cold advection in the west side of the Bering cyclone worked to sustain the low temperature over the north-western Pacific. As the result, the strong ∇T in $30 \sim 40^{\circ}\text{N}$ zone over the Pacific, and the large Continent-Pacific temperature contrast in $40 \sim 70^{\circ}\text{N}$ were maintained throughout the Baiu period (Fig. 12).

Peak Baiu period

The rise of 850 mb temperature was still large over the high-land area in June $\sim$ July ($\sim 8^{\circ}\text{C}/\text{month}$). The area of high temperature protruded northward from the Tibetan Plateau to the Sibirsk Plateau ($\sim 70^{\circ}\text{N}/100^{\circ}\text{E}$). This temperature rise was partly due to the warm-air advection by the southerly wind in the west side of the Baiu ridge.

In accordance with the full development of the Baiu trough, the tongue-shaped area of low temperature extended from the Bering Sea to the Japan Sea, the Yellow Sea, and farther to the central part of China ($\sim 35^{\circ}\text{N}/105^{\circ}\text{E}$). The formation of cold zone was due to the cold-air advection by the Baiu-trough N $\sim$ NE wind. The large cloudiness in the Meiyu and Baiu frontal zone also prevents the warming due to isolation.

The 340 K isoline of θe_{850} , which indicated the northern boundary of the tropical marine airmass, was located along $\sim 35^{\circ}\text{N}$. The narrow area of nearly moist-neutral stratification ($\theta e_{700} - \theta e_{850} \approx 0$) was extending along $\sim 35^{\circ}\text{N}$ from 100°E to 135°E . The successive development of convective clouds in the Baiu/Meiyu frontal zone worked to form the zone of moist-neutral layer. Similar feature was analysed for the other years by Matsumoto *et al.* (1971) and Akiyama (1973).

Fig. 11 The 10-day averaged 850 mb equivalent potential temperature (θ_{e850}) and ($\theta_{e700} - \theta_{e850}$, dashed lines) for May I, Jun I, Jul I and Jul III, 1979.

Post Baiu period

The temperature field changed rapidly in the transitional period between the Baiu period and the middle summer. Concurrent with the decay of the Baiu ridge, Baiu trough and the Bering cyclone, and with the northward shift of the Pacific anticyclone, the long-wave pattern of thermal field changed into the zonal pattern with weak ∇T in Jul III. The large temperature difference between the Continent and the Pacific disappeared too (Fig. 12).

Difference between Meiyu and Baiu front

The latitude-time section of 10-day averaged 850 mb temperature along 110, 130 and 150°E meridians are presented in Fig. 13. The data at grid point with 5°Lat. interval were used.

The temperature variation was large over the Continent (110°E). The period of high temperature in 30 ~ 60°N roughly coincided with the peak period of the Baiu ridge. The largest

temperature rise occurred around May III (transition from the pre- to the early-Baiu period) and the secondary rise around Jun III (transition from the early- to peak-Baiu period). Along 110°E, the maximum zone of ∇T (~ 10 K/1000 km, in N-S direction) was in 50 ~ 70°N zone. The Meiyu frontal zone (~ 35°N) was located in the area of very weak ∇T .

Along 130°E, the temperature rise was gradual in 20 ~ 40°N zone. The maximum ∇T around 70°N was ~ 10°C/1000 km, while ∇T in 30 ~ 60°N, including the Baiu frontal zone, was ~ 5°C/1000 km.

Over the Pacific (150°E), temperature change was small during the Baiu season (May III ~ Jul II). The temperature rise in 45 ~ 60°N zone in Jul II ~ III was associated with the northward displacement of the Pacific anticyclone and with the weakening of the Bering cyclone. Strong ∇T of ~ 10°C/1000 km was maintained around

Fig. 12 The longitude-time section of 10-day averaged 850 mb temperature (T_{850}) at 50 and 40°N.

40°N during the peak period of Baiu (Jun II ~ Jul II).

The aforementioned regional difference of the baroclinicity (thermal gradient) of the Meiyu/Baiu front had strong influence on the evolution of the frontal disturbances. Because of the weak baroclinicity in the Meiyu front and the western part of Baiu front, the development of the frontal depressions was very slow and consequently the front remained quasi-stationary. Some of the weak frontal depression began to develop when they moved over the Pacific where the thermal gradient in the Baiu front was relatively large.

Fig. 13 The latitude-time section of 10-day averaged 850 mb temperature at 110, 130 and 150°E.

6. Moisture field and moisture flux

Moisture field

Fig. 14 shows the 10-day averaged 850 mb specific humidity (q_{850}) for May I, Jun I, Jul I and Jul III. Fig. 15 presents the latitude-time section of q_{850} along 110, 130 and 150°E meridians. Data at grid points with 5°Lat. interval were used for Fig. 15.

The time variation of q_{850} was very large around India. It increase rapidly from ~ 5 g/kg (May I) to ~ 15 g/kg around the onset of monsoon (Jul I). On the one hand, the moisture

Fig. 14 The 10-day averaged 850 mb specific humidity (q_{850}) for May I, Jun I, Jul I and Jul III, 1979.

variation was small over the subtropical ~ tropical Pacific, the Indo-China Peninsula and the Bay of Bengal. The q_{850} over these areas was 12 ~ 14 g/kg throughout the Baiu season. The q_{850} in 40 ~ 70°N zone increased with the rate of ~ 2 g/kg/month in May ~ July. The zonal pattern of the moisture field was seen in this zone.

The Meiyu and Baiu frontal zone are identified in the moisture field as the zone of maximum ∇q_{850} (5 g/kg/1000 km). The largest ∇q_{850} of 5 g/kg/500 km was seen in the peak-Baiu period (Jun III ~ Jul I). Over the Continent (~ 110°E), the rise of q_{850} in 30 ~ 40°N occurred around May III (transition to the early Baiu period) and around Jun III (peak period of Baiu and the onset period of monsoon). However, the largest moisture gradient (~ 8 g/kg/1000 km) was maintained in 30 ~ 35°N zone. This indicates the effect of the Tibetan Plateau to block the northward intrusion of moist air. The Baiu-

trough-northeasterly flow also tends to block the northward intrusion of moist air. The moisture gradient in the Baiu frontal zone around 130°E was much smaller than these around 110°E.

Over the Pacific (150°E), the moisture increase in the Baiu period was very small. The strong ∇q_{850} (~ 4 g/kg/1000 km) was maintained in 30 ~ 40°N zone. This zone of maximum ∇q_{850} coincided approximately with that of maximum ∇T_{850} . The low- q advection in the west side of the Bering cyclone sustained the moisture gradient over the Pacific.

Moisture flux

Fig. 16 shows the maps of 10-day averaged 850 mb moisture flux (Vq_{850}) for May I, Jun I, Jun III and Jul III. The common feature of the moisture-flux fields seen in May ~ July was the zone of maximum flux along the west ~ north-western periphery of the Pacific anticyclone.

Fig. 15 The latitude-time section of 10-day averaged 850 mb specific humidity (q_{850}) along 110, 113 and 150°E meridian.

This maximum zone shifted northward with the seasonal northward advancement of the Pacific anticyclone. The moisture convergence in the Meiyu front was seen along the northern boundary of the area of southerly moisture flux, while that in the Baiu front was seen along the northern boundary of the area of southwesterly moisture flux.

A large seasonal change of Vq was observed over India. The flux was small in May. Around Jun I, with the development of the low-pressure area to the south of the Tibetan Plateau, the

moisture flux in the cyclonic flow around 20°N over India, the Bay of Bengal and Indo-China areas intensified.

Around the onset of monsoon and the peak period of Meiyu/Baiu precipitation (Jun III), the moisture flux increased rapidly over India. The zone of maximum Vq over India (20–15°N) extended eastward to the Bay of Bengal, Indo-China and farther to ITCZ over the South China Sea. At the same time, the southerly Vq from the South China Sea to South China increased.

In the post-Baiu period (and the break monsoon period), the moisture flux decreased rapidly over India, the Bay of Bengal, the South China Sea and South China.

7. Intraseasonal variation of the Pacific anticyclone and Baiu front

The northward advances of the Pacific anticyclone and the Baiu frontal zone (cloud zone) are the basic seasonal change over the East Asia. We also found the distinct intraseasonal variations of these systems superposed on the seasonal change.

The longitude-time section of Z_{850} along 40°N (Fig. 5, bottom) indicates quasi-periodic variations of the Pacific anticyclone with an approximate 40-day period. The maximum westward extension of the Pacific anticyclone was seen in Jun II and Jul III, while the eastward retreat in May II and Jul I. In the latitude-time section of Z_{850} along 130°E (Fig. 17), the maximum northward advance of the Pacific anticyclone was seen around Jun II and Jul III, and the southward retreat around May III and Jul II.

Fig. 18 is the latitude-time section of 5-day and 2°Lat × 2°Lon area averaged high-cloud amount (C_H) along the 120 and 140°E meridians. Note the Baiu cloud zone extending around 35°N and the ITCZ cloud zone around 10°N. These two major cloud zones were separated by the cloudless area over the subsidence area of the Pacific anticyclone.

The periods of maximum ITCZ cloud amount occurred in May I, Jun III and Aug I, while the minimum periods in May II and Jul II. The peaks of ITCZ cloud amount accorded with the peaks of the monsoon precipitation over India (Jun III and Aug I) while the minimum to the monsoon breaks. The north-south displacement of the

Fig. 16 The 10-day averaged 850 mb water-vapor flux (Vq_{850}) for May I, Jun I, Jun III and Jul III, 1979.

Fig. 17 The latitude-time section of the 10-day averaged 850 mb height (Z_{850}) along 130°E meridian.

cloudless zones (subsidence area of the Pacific anticyclone) and the Baiu frontal cloud zone were related to the convective activity of ITCZ.

The cloudless zone and Baiu cloud zone advanced northward in the peak periods of ITCZ cloud zone (May I, Jun III and Aug I) while retreated southward in the minimum periods of ITCZ cloud cover (May II and Jul II).

The feature along 160°E (not presented) was similar to that at 140°E. On the one hand, the situation along 120°E was somewhat complicated, because of the combined effects of the Baiu-trough-northerly winds, monsoon westerly and southeasterly winds in ITCZ on this particular area. The peak of ITCZ cloud cover occurred in Jun II and Aug I, while the maximum of Baiu cloud cover in Jun III and Jul II. These peak periods accorded approximately with these in 140°E.

We have thus far emphasized the influence of active-break cycle of monsoon on the Baiu front activity through the variations of the ITCZ and the Pacific anticyclone. However, the mechanisms and processes of these influence remain unknown.

Fig. 18 The latitude-time section of the 5-day averaged high-cloud amount (C_H) along 120 and 140° E meridian.

In spite of the prominent intraseasonal variations of the Baiu frontal cloud zone, associated precipitation peaks were not necessarily obvious in the time-series data of precipitation (Fig. 1), except for the prominent precipitation peak in Jun III. It is, then, inferred that the intense Baiu precipitation was more closely related with smallscale conditions rather than very large-scale circulations associated with the ~ 40-day period oscillations.

8. Baiu trough, Baiu front and depressions in Baiu season

In the previous sections, the large-scale circulations in the Baiu season have been described

on the basis of 10-day averaged fields. Some description pertaining to individual disturbances, which are superposed on the time-averaged large-scale systems, may be necessary. Here, we summarize the features in the 10-day averaged field in the peak period of Baiu (Jun III) and describe the features of individual depressions in relation to the time-averaged field.

Fig. 19 illustrates schematically the large-scale features at 850 mb. The axis of Baiu ridge, Baiu trough and the Baiu shear line are illustrated in this figure. The axis of the Baiu-trough-northerly wind, Indian monsoon westerly wind, the South China Sea southerly wind-and SW ~ WSW wind along the periphery of the Pacific anticyclone are indicated by the arrows. Hatching over the Pacific represents regims of large high-cloud amount ($C_H>0.4$) and that over China indicates regions of intense precipitation exceeding 100 mm/10 day. (Precipitation area was reproduced from Luo and Yanai, 1983.)

The Meiyu frontal precipitation zone was related with the Baiu shear line. The Baiu frontal cloud zone was located ~ 1500 km to the south of the Baiu-trough and along the northwest ~

Fig. 19 The schematic illustration of the Baiu ridge, Baiu trough, Baiu shear line and the Bering cyclone at 850 mb for Jun III. The axis of Baiu-trough-northerly wind, Indian monsoon westerly wind, the South China Sea southerly wind and SW ~ WSW wind along the periphery of the Pacific anticyclone at 850 mb are indicated by arrows. Hatching over the Pacific indicates the zone of large high-cloud amount ($C_H>0.4$). Hatching over China indicates area of precipitation exceeding 100 mm/10 day (reproduced from maps f and g in Fig. 3 of Luo and Yanai, 1983).

northern periphery of the Pacific anticyclone.

Fig. 20 shows the location of disturbances, which are identified by a closed isobar or height contour, on 700 mb and the surface map at 12 GMT of each day in Jun III. The jet-stream axes on the 10-day averaged 300 mb wind field are indicated by arrows in the top diagram. The disturbances shown in Fig. 20 are classified into the following four categories from their scale, vertical structure and evolution process;

(1) Synoptic-scale disturbances around the polar jet stream (polar frontal disturbances).

(2) Weak disturbances located to the south of the polar jet stream (middle latitude disturbances).

(3) Weak subsynoptic-scale disturbances along the time-averaged Baiu frontal cloud zone

(Baiu frontal disturbances).

(4) Tropical depressions over the Pacific and the South China Sea.

The category-(1) disturbances were associated with the westerly trough in the polar frontal region. Some of them developed into the synoptic-scale cyclones over the northwestern Pacific and the Bering Sea. They appeared as a stationary cyclone (the Bering cyclone) on the 10-day averaged field.

The category-(2) disturbances were formed in the north side, or around the eastern foot of the Tibetan Plateau. Usually, they did not develop into deep synoptic-scale cyclone.

The category-(3) disturbances usually develop as subsynoptic-scale (meso- α -scale) cloud clusters in satellite cloud images, and do not develop into deep depressions. The cyclonic circulation of these disturbances are not always identified at 850 or 700 mb. In spite of the intense precipitation over China, such cloud clusters were not necessarily analyzed as depressions on the conventional synoptic maps. This would be due to the slow deepening of the depression under the condition of very weak baroclinicity in the Meiyu frontal zone. Usually they began to develop into depressions in the area to the east of $130 \sim 135^\circ\text{E}$. The cloud systems associated with them appeared as the Baiu frontal cloud zone in the 10-day averaged maps. In this sense, the Baiu front may be regarded as the locus or a train of these subsynoptic-scale depressions. (See Matsumoto *et al.*, 1970; Ninomiya and Akiyama, 1972; Ninomiya *et al.*, 1981; Akiyama, 1978, 1984 for the evolution of Baiu frontal depressions.)

The synoptic situations during the Baiu season vary substantially with time. The situations at a certain synoptic-time were not necessarily the same as these in the time-averaged field. More detailed studies on the relation between the time-averaged large-scale circulation systems and the individual disturbances superposed on the basic flow are necessary in order to understand the physical processes occurring during the Baiu season.

9. Concluding remarks

The large-scale aspects of the Baiu/Meiyu

Fig. 20 The locations of 700 mb and the surface disturbances at 12 GMT of each of 10 days within Jun III, 1979. The dashed lines indicate the analyzed domain. The arrows show the jet stream axis on the 10-day averaged 300 mb wind field.

in 1979 were studied on the basis of 10-day averaged fields. The results are summarized as follows:

(1) The large-scale circulations changed rapidly before, during and after the Baiu season. In the middle and high latitudes, the noteworthy features are the development of a warm ridge (Baiu ridge) over the Mongol ~ Sibirsk Plateaus and a cold trough (Baiu trough) extending from the Bering cyclone to China.

(2) The lower tropospheric circulations during the Baiu season were characterized by Baiu-trough-northern ~ northeasterly winds, southerly winds over the South China Sea and South China, low-level-jet-like strong WSW winds along the periphery of the Pacific anticyclone, and the Indian monsoon westerlies which extended eastward and turned to southerly winds over the South China Sea.

(3) Temperature in the lower troposphere increased rapidly over the Asiatic continent in May ~ June. The temperature gradient over South China decreased and the convective stable condition changed into convectively unstable condition. On the other hand, the temperature increase was less significant over the Pacific north of 35°N because of the cold sea surface temperature and cold air advection in the rear of the Bering cyclone. Consequently, a large temperature difference between the Asiatic continent and the Pacific was maintained.

(4) The Tibetan Plateau and the Baiu-trough-northerly-wind prevented the northward intrusion of moist airmass and sustained the strong moisture gradient along the Meiyu frontal zone. Over the Pacific, a strong thermal and moisture gradient in $30 \sim 40^{\circ}\text{N}$ was maintained by the northerly wind in the rear of the Bering cyclone.

(5) While the Meiyu front was related to low-level convergence along the Baiu shear line between the Baiu-trough-northerly-winds and the South China Sea southerly winds, the Baiu front was located ~ 1500 km south from the Baiu trough and along the northern periphery of the Pacific anticyclone. The convergence in the Baiu frontal zone was associated with confluence of southwesterly winds to the zone of maximum WSW wind.

(6) The Meiyu front and the western part of

the Baiu front were characterized by a weak thermal gradient, strong moisture gradient and convectively unstable stratification. Subsynoptic-scale disturbances in the frontal zone were recognized as subsynoptic-scale cloud clusters. Some of them developed into Baiu frontal depressions in the eastern part of Baiu front where the thermal gradient was relatively large.

(7) The seasonal northward advance of the Pacific anticyclone and Baiu front was the basic seasonal change during the Baiu season. The quasi-periodic (~ 40 day-period) intraseasonal variations were seen superposing on these seasonal changes. In the peak periods of the cloud cover in ITCZ in $120 \sim 160^{\circ}\text{E}$, the Baiu front advanced northward and cloud cover attained maximum value. The peak of Indian monsoon precipitation coincided approximately with the peak period of ITCZ and Baiu front activity.

(8) During the middle summer, the Pacific anticyclone moved northward, and the Baiu ridge and Baiu trough disappeared. Simultaneously, the geopotential height and temperature patterns changed to zonally symmetric pattern with a weak horizontal gradient.

The results of the present analysis are to be compared with the result of numerical prediction experiments of Baiu by Nakamura, Hasegawa and Ninomiya (1985). They performed 15-day prediction experiment using a global spectral model (12-level, triangular wave number truncation at wave number 42) from the initial condition at 12 GMT 15 June 1984. In their experiment, the Baiu front, which was defined as the zone of strong $\nabla\theta_e$, was well simulated over China. When the Tibetan Plateau was excluded from the model, the southerly wind prevailed over China associated with the development of cyclones and Baiu front disappeared. This indicates the role of the Tibetan Plateau in the formation of Baiu front.

In the model, the Bering cyclone did not develop and the unrealistic southerly winds prevailed and, thus, low temperature over the Pacific north of $\sim 35^{\circ}\text{N}$ was not maintained and the Baiu front over the Pacific became obscured. This indicates that the Bering cyclone and the associated cold northerly winds over the cool northwestern Pacific is one of the key factors

for the formation of the eastern half of the Baiu front. These simulation experiments support the inferences in the present observational study that the Tibetan Plateau, the Bering cyclone and the Baiu trough are equally important for the maintenance of the Baiu/Meiyu front.

The Baiu situations vary from one year to another. Ninomiya and Mizuno (1985) described the year-to-year variations of the surface temperature during the Baiu and summer season over Japan for 1951 ~ 1980. Further studies are needed to compare the features in 1979 with those in other years and identify the common features, besides the year-to-year variations.

Acknowledgement

This work was made mainly when the authors were in Electronic Computation Center of JMA. The authors acknowledge the discussions with Dr. H. Nakamura and Mr. N. Hasegawa of Numerical Prediction Division, JMA and Dr. T. Akiyama of Meteorological Research Institute. They acknowledge the comments from reviewers in preparing the final paper.

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1979年梅雨期東アジアの大規模場の特徴

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1979年梅雨期東アジアの大規模場の特徴と推移を主として10日平均場にもとずいて記述した。従来充分に解析されていなかった中高緯度の状況にも注目した。

梅雨初期、大規模場は大きく変化する。チベット高原北部から北に伸びる高温リッジ（梅雨リッジ）とベーリング海低気圧から西南西に中国に伸びる低温トラフ（梅雨トラフ）が発達する。中国大陸では下部対流圏の気温が急上昇し、気温傾度は減少し、対流不安定成層となる。一方 35° N以北の冷たい太平洋ではベーリング海低気圧西方の寒気移流により気温上昇は阻止される。このため著しい大陸～太平洋間の気温差が生じる。

対流圏下部の循環は梅雨トラフ西側の北東風（梅雨トラフ北東風系）、太平洋高気圧縁辺の下層ジェットの西南西風系、インドモンスーン西風につらなる南シナ海風系によって特徴づけられる。後者の二風系は日本列島、中国域への水蒸気流入をもたらす。

中国の梅雨前線は梅雨トラフ北東風と南シナ海南風との間に形成される梅雨シアラインに密接に関係する。日本附近の梅雨前線は梅雨トラフの南～1500kmに位置し、南西風の西南西強風軸への合流収束域に位置する。

中国～西日本域の梅雨前線帯は水蒸気傾度は大きく気温傾度は弱い。東日本以東では気温傾度もやや大きい。このため前線帯の中間規模低気圧の発達～ 135° E以東でみられる。なおベーリング海域で発達する低気圧の多くは極前線帯のトラフにともなう低気圧である。

太平洋高気圧と梅雨前線の北上は梅雨期の基本的季節変化である。これに重なって～40日周期の準周期的変動がみられる。ITCZの雲量極大期に梅雨前線が北上し、その雲量・雨量も増加する。特に6月下旬のインドモンスーン降雨の極大期には南シナ海ITCZの雲量が増加し、梅雨前線活動も増加した。

チベット高原、梅雨トラフ北東風は中国～ 35° N以北での低水蒸気量を維持し、～ 35° N帯に強い水蒸気傾度（梅雨前線）を維持する。太平洋域ではベーリング海低気圧西方の北風による移流が $35\sim40^{\circ}$ Nに気温傾度と強い水蒸気傾度（梅雨前線）を保つ。

梅雨末期、太平洋高気圧と上層の高気圧帯は北上し、梅雨リッジ、梅雨トラフは急速に消失し、高度場・温度場はゾーナルパタンに変わり、傾度は減少し、盛夏となる。

上記のチベット高原、梅雨トラフ、ベーリング海低気圧の梅雨前線生成維持に関する役割についての推論は、中村・長谷川・二宮（1985）の予報実験の結果からも支持される。