Effects of Blocking Anticyclones in Eurasia in the Rainy Season (Meiyu/Baiu Season)

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Abstract

Distribution of BAs in Eurasia during the Meiyu/Baiu season and some possible influences of BAs on the behavior of the MB frontal zone were examined through statistical analyses. Then detailed analyses were made for a case in late June 1982.

BAs appear with higher frequency in the regions of 31–60°E, 91–110°E and 131–150°E in the latitudes of 50–70°N. The maximum frequency is found in the region of 131–150°E.

The appearance frequency of BAs in region of 50–70°N/81–120°E (Region B) showed a positive significant correlation with the persistency of the Baiu period in Japan. On the other hand, the appearance frequency of BAs in the region of 50–70°N/121–160°E (Region C) showed a positive correlation with both the persistency of the Meiyu period and the rainfall amount during that period in Central China.

A statistical analysis suggests that the existence of cold air in the lower layer in 32.5–35°N/112.5–117.5°E (corresponding to the area just to the north of the Meiyu front), largely associated with a BA in Region C, is an important factor in activating the Meiyu front in Central China, and in enhancing the lowlevel southerly wind component in South China. A case study for June 1982 showed that the cold air intrusion toward Central China in the situation of Type C occurs mainly in the lower layer, and is accompanied by the development of a baroclinic instability wave around 50°N/100–110°E. The formation of the Type C situation is a favorable condition for cold air coming southward to the Meiyu frontal zone.

On the other hand, there was a Rossby wave-like (height) anomaly pattern propagating from the Okhotsk Sea to the tropics through Japan shown by the presence of a BA in Region C in June. Although forcing processes have not been clarified yet, a case study in late June 1982 suggests that the wave was amplified around the Lake Baikal to the Okhotsk Sea area. The propagation might result in a negative anomaly of geopotential height at 500 mb level to the east of Japan, a southward shift of the Baiu front and weakening (or southward shift of) the sub-tropical high in nearby regions. The present paper shows the different effects of the Type C situation on climatological features of the Meiyu front from those of the Baiu front.

1. Introduction

Blocking anticyclones (BAs) develop over the middle and high latitudes of Eurasia during the early summer every year (Sasaki, 1965; Yoshino, 1977; Zhu *et al.*, 1979) and they affect the weather situation in the Meiyu season and the Baiu season when the stationary front stays over the Changjiang River Basin and Japan. Many studies have been made on the effects of BAs on the Meiyu and the Baiu.

For example, the role of Okhotsk High associated with a blocking anticyclone (BA) over East Siberia in the Baiu rainfall in Japan has been studied extensively in Japan since the 1950's (Suda and Asakura, 1955; Yoshino, 1963). Ooi (1969) stated that if

Okhotsk High is not formed in the troposphere, the rainfall in Japan will be scarce during the Baiu season. In contrast, Ninomiya and Akiyama (1980) came to a conclusion that Okhotsk High plays a secondary role in forming the Baiu front, but plays an important rôle in influencing the weather of northeast Japan during summer. Recently, the latter opinion has been more generally accepted because of the fact that the Baiu front remains active without a significant negative temperature anomaly to the north of the front associated with Okhotsk High (*e.g.*, Fig. 17 of Ninomiya and Mizuno, 1987).

According to Sasaki (1965), BAs occur more frequently over Europe and the East Pacific than over East Asia. The persistent period is shorter and the day-to-day stability is weaker over the Far East.

Although the rainfall activity of the Baiu front in Japan (the Meiyu front in Central China) is controlled largely by the huge moisture transport in the lower layer from the sub-tropical high area to the south of the front (*e.g.*, Akiyama, 1975; Ninomiya, 1984), Sasaki (1965) argued that a BA over the Far East has a considerable influence on weather in the middle latitudes and should not be ignored in weather forecasting.

In China, during the rainy season in early summer, three types of BAs have been widely known as follows: (i) A BA over Lake Baikal, (ii) Simultaneous BAs in the two regions near the Ural Mts. and Yakutsk, and (iii) BAs over three regions: near Eastern Europe, Lake Baikal and Yakutsk simultaneously (Zhu *et al.*, 1979). If there occurs at least one of these three types for a prolonged period, the Meiyu develops markedly.

But even now, how BAs over the different regions of the Eurasia continent affect the behavior of the Meiyu and Baiu (MB) frontal zone has not yet been clarified. Thus, the distribution of BAs during the Meiyu/Baiu season (MBS) and the effects of BAs in each region on the behavior of the MB will be examined in the present study. The MB frontal zone is affected by the higher-latitude systems in various processes, such as Rossby wave-like propagation, southward intrusion of cold air in the lower layer, that of the upper-level cut-off low, and so on. The latter part of the present study will discuss the effects of BAs in different regions on the MB frontal zone, based on a case study for June 1982.

Section 2 gives data sources used in this study, and the climatological feature of the appearance of BAs during the MBS will be analyzed in Section 3. The correlation between the MB and BAs based on data for 14 years will be presented with special attention paid to the rôle of a BA in the Okhotsk Sea region (in Type C) in Section 4. In order to investigate the relationship between the Baiu and a BA, a statistical analysis and a case study will be made for Rossby wave propagation associated with a BA around the Okhotsk Sea in Section 5. Section 6 of this paper describes the process of cold air intrusion from high latitudes to the Meiyu frontal zone associated with a BA around the Okhotsk Sea by a case study.

2. Data

The following data sets were used in this study:

(1) Precipitation and number of days during the MBS rearranged as follows: (i) Mean values of precipitation, number of persistent days¹ during the

¹Mean values of precipitation and persistent days during the Meiyu/Baiu season are defined as the mean values of the precipitation and days from the onset to ending of the rainy season (Meiyu/Baiu season) averaged from the stations as shown in Fig. 1, which represents the average precipitation and

Baiu season for the years of 1971–1984, which is obtained from the average value for ten stations every year quoted from the Meteorology Yearbook, 1989 published by the Japan Meteorological Agency (JMA). The ten stations are Kagoshima, Fukuoka, Hiroshima, Takamatsu, Osaka, Nagoya, Tokyo, Niigata, Sendai and Aomori, from which the mean climatological condition of the Baiu over Japan is obtained. (ii) Mean values of precipitation and the number of persistent days at five stations in the area along the middle and the lower courses of the Changjing River during the Meiyu season for the years 1971–1981 quoted from the Meteorological Data for 500 Years' Xerasium in China published by the Meteorological Publishing House, China. The five stations are Shanghai, Nanjing, Wuhu, Jiujiang, and Hankou. (iii) Precipitation and number of persistent days at Nanjing during the Meiyu season for the years 1982–1984, provided by Nanjing Observatory to be supplied for the missing data in other stations since the precipitation and the onset and cessation of the Meiyu among the stations along the Changjiang River are close every year, as pointed out by Zhu *et al.* (1979). The stations used in this study are shown in Fig. 1

(2) Outgoing Longwave Radiation (OLR): twice-daily data at $2.5^\circ \times 2.5^\circ$ lat./long. grid points during June and July, 1979–1984, measured by polar-orbiting satellites of the NOAA series.

(3) Pentad-mean 500 mb height at $10^\circ \times 10^\circ$ lat./long. grid points, compiled by the Long-range Forecast Division of the JMA during June and July of 1979–1984.

(4) Twice-daily (0000 and 1200 GMT) 500 mb level height and temperature with grid points of $2.5^\circ \times 2.5^\circ$, during June of 1982, produced by the U.S. National Meteorological Center (NMC).

(5) Weather charts: daily weather charts at 500 mb at 1200 GMT, June and July of 1971–1984, published by JMA.

3. Climatological features of the appearance of the Blocking Anticyclones

3.1 Method for identification of blocking anticyclones

In this section, the statistical characteristics of BAs are described. According to Rex (1950), the definition of a BA is as follows: (i) The basic westerly current must split into two branches, (ii) Both branches should be clearly recognized, (iii) The double jet streams must spread over at least 45° of longitude, (iv) One branch stream should change suddenly from zonal flow to meandering flow, and (v) Such a situation should continue for at least 10 days. The definition of the blocking anticyclone in East Asia by Sasaki (1965) is looser, as follows: (i)

persistence of the Meiyu in China and the Baiu in Japan.

Fig. 1. Distribution of stations where precipitation data were used in the present study.

Brancing jet streams must exist, and (ii) The situation must be maintained for at least three days. The definition by Rex was too strict for the BAs occurred over at East Asia, especially in summer, because they usually last for fewer days than those which occur over Europe. The shorter BAs are thought to play an important rôle in weather situations associated with the MB front. Since the definition by Sasaki is too loose, the definition is strengthened by adding Rex (1950a, b) and Zhu *et al.* (1979). The definition of a BA in the present study is as follows: (i) At the 500 mb level a high center with closed isohypse exists at the middle and high latitudes at 50–70°N, not simply a case when a large positive anomaly of geopotential height at 500 mb level from the climatic value is observed, (ii) The high pressure area is maintained for at least three days and the phase speed of the high's center is less than 7° longitude per day, and (iii) During this period, the branch, separated wider than 40° in longitude, must last for at least two days.

Following this definition, statistics of BAs were made using weather charts for the 500mb level prepared by the JMA for the area of 21–160°E and 50–70°N during June and July of 1971–1984. The mean period of the Baiu averaged in Japan for each year was adopted as the period of the MBS, since the onset (withdrawal) of the Meiyu in Central China was later (earlier) in every year than that of the Baiu in Japan, as presented in Table 1. The total number of days of the MBS over 14 years (referred to as the DSS) was 596 days (42.5 days/MBS). 98 cases of the BA generation were counted in the period. In the

longest case, a BA lasted for 23 days, *i.e.*, 14 June to 6 July in 1983. The mean number of persistent days for a BA was 5.9 days.

3.2 The frequency of appearance of BAs

Figure 2 shows the ratio of the number of days when centers of the BAs were located in a given 10° longitude to the total number of days when they were located in the area 50–70°N and 21–160°E, during the MBS. When a BA moved to a new 10° longitude region both regions were included in their respective amounts. When two or three BAs occurred on the same day in different regions, the number of persistent days of a BA were counted for each region, respectively. The maximum appearance of BAs is found at 131–140°E around Yakutski and the region of high frequency extends to 150°E. The second group of high frequency appears at the longitude band of 91–110°E (around Lake Baikal) and the third group at 31–60°E (around the Ural Mts.); as pointed out by Zhu *et al.* (1979). They did not analyze the statistical distribution of BAs and did not discuss it further. According to the three areas of high frequency in Fig. 2, the BAs which appeared in the longitude belt of 21–80°E (Region A), 81–120°E (Region B) and 121–160°E (Region C) in daily maps are hereafter referred to as Types A, B, and C, respectively.

Now we will compare the frequency of appearance of BAs in each type in the MB (as defined above) with that in the no-MBS from June to July. The total number of days when a BA was identified in the MBS (referred to as DBS) in the entire period from June to July (DBT) was counted for each type.

Table 1. The period during MBS.

Year	Period of Meiyu	Period of Baiu	Year	Period of Meiyu	Period of Baiu
1971	6.9–6.15	6.3–7.28	1978	6.10–6.15	6.10–7.4
1972	6.20–6.30	6.8–7.19	1979	6.19–7.23	6.7–7.26
1973	6.16–6.26	6.5–7.7	1980	6.9–7.22	6.5–7.21
1974	6.10–7.19	6.6–7.22	1981	6.25–7.2	6.9–7.14
1975	6.16–7.17	6.5–7.16	1982	6.15–7.1	6.14–7.31
1976	6.21–7.16	6.6–7.19	1983	6.14–7.18	6.11–7.25
1977	6.9–6.18	6.7–7.18	1984	6.12–7.6	6.8–7.17

Fig. 2. Occurrence frequency of BAs in the area 21–160°E and 50–70°N during MBS, 1971–1984. Details are referred to in the text.

Then the total number of days with a BA in the period which did not correspond to the MBS from June to July (DBN) was derived from $DBN = DBT - DBS$, for each type. The relative frequencies of appearance of BAs for these periods was also calculated as follows:

$$RBS = DBS/DSS \quad (1)$$

and

$$RBN = DBN/(D67 - DSS), \quad (2)$$

where D67 denotes the number of days from 1 June to 31 July during the 14 years (equal to 854 days). The results are presented in Table 2.

The total number of days when a BA was identified in the MBS (DBS) was 180 days and 220 days from 1971 to 1984 for Types B and C, respectively, while DBN totalled only 21 days and 49 days, respectively. Comparing the ratios RBS and RBN, a BA in Region B or C tends to appear more frequently during the MBS than in the non-MBS from June to July. However, the RBS and RBN for Type A, were nearly equal to each other, although the values attained were about 0.30. These results suggest that the existence of a BA in Region B or C is one of

Table 2. Comparison of total number of days when a BA was identified for each type between the MBS and the non-MBS in June and July. Units of DBS and DBN are a day. As for the notations, refer to the text. RBS and RBN are also listed in this Table with non-dimension.

Type:	A	B	C
DBS (days)	182	180	220
RBS	0.31	0.30	0.37
DBN (days)	72	21	49
RBN	0.28	0.08	0.19

the important features which promotes the situation of the MBS.

Sometimes, BAs were located simultaneously in different regions, *i.e.*, Regions A and C, Regions A and B, Regions B and C, or Regions A, B, and C. But BAs coexist generally for a shorter time. The total number of days when BAs were located simultaneously in more than two of the regions mentioned above was 68 days, 26 days, 37 days, and 5 days, respectively, and they were much less frequent than DBS for each type (see Table 2). Thus, the features of typical events when no more than two BAs coexisted in the different regions will be treated in the following discussions.

3.3 Composite patterns of BAs for the three types

Figures 3a, 3b, and 3c show the composite maps for Type A, Type B, and Type C, respectively, during the MBS, 1979–1984, based on the pentad-mean 500mb height at every $10^\circ \times 10^\circ$ latitude/longitude grid point mentioned in Section 2. Pentads for a composite map of Type A were selected so that the number of persistent days of Type A was at least 3 days in a pentad and the high centers of BAs were limited to the longitude belts of 36–55°E. Those for Types B and C were selected in a similar way but for the longitude belts of 91–110°E and 131–150°E respectively. The total numbers of the pentads used for the composite were 5, 12, and 11 for Types A, B, and C, respectively.

Type B has the largest spatial scale in the zonal

Fig. 3. The composite map of pentad 500 mb height (gpm) for BA in Type A (a), Type B (b) and Type C (c). The contour interval of 500 mb height is 40 gpm (thin lines). The thick lines show the troughs.

direction among the three types. The BA is centered at $60^{\circ}\text{N}/100^{\circ}\text{E}$. The troughs to the west and to the east of the BA of Type B exist at about 40°E and 130°E , respectively, and the wavelength of the BA is estimated to be about 90° in longitude. Despite Type A, whose center is located at $60^{\circ}\text{N}/50^{\circ}\text{E}$, having a wavelength of 90° in longitude, (the troughs to its east and west are around 20°E and 100°E), there is also another trough around 70°E . Type C, in which the high center is located at $60^{\circ}\text{N}/130^{\circ}\text{E}$, has troughs around 110°E and $140^{\circ}\text{--}160^{\circ}\text{E}$, respectively, with the smallest wavelength of 50° longitude.

Figure 3b shows that a trough to the east of a BA of Type B, extending from north of the Okhotsk Sea

to the Northeastern district of China, is located at roughly the same position as that of the “Baiu trough”, and the BA in Type B roughly corresponds to the “Baiu ridge”, as pointed out by Ninomiya and Muraki (1986) and Ninomiya (1989). As for Type C, the trough to the west of the BA (about 110°E) extends southward to 40°N with only narrow longitudinal scope. In addition, a weak trough is found to the south of the BA of Type C, which indicates the approximately out-of-phase relationship of geopotential height at 500 mb level along about 140°E . On the other hand, although another ridge exists around 140°E in Type A, as in Type C, the ridge line extends more southward to about 30°N .

Table 3. Correlation coefficients between the number of persistent days of BA during MBS (a) and June to July (b) in respective types and number of persistent days of MB or rainfall during MBS. The mark * (**) shows that value of the coefficients is over 90 % (95 %) confidence level.

(a)				
Number of persistent days of blocking anticyclone in Type:	Number of persistent days of		Rainfall	
	Meiyu in China	Baiu in Japan	Meiyu in China	Baiu in Japan
Type: A (MBS)	0.10	−0.02	0.08	0.33
Type: B (MBS)	0.32	0.69**	0.37	0.22
Type: C (MBS)	0.54**	0.45	0.50*	0.23

(b)				
Number of persistent days of blocking anticyclone in Type:	Number of persistent days of		Rainfall	
	Meiyu in China	Baiu in Japan	Meiyu in China	Baiu in Japan
A (JUNE to JULY)	0.02	0.04	−0.04	0.19
B (JUNE to JULY)	0.23	0.48*	0.17	0.31
C (JUNE to JULY)	0.62**	0.42	0.60**	0.21

Thus, the geopotential height at the 500 mb level around Japan in Type A seems to present some different weather situations from Type C.

4. Statistical relationship of the appearance of the BAs to the presence of the Meiyu/Baiu front

4.1 Correlations

The correlations between the total number of persistent days of BAs in the MBS (DBS) or June to July (DBT), and the number of persistent days of the Meiyu/Baiu (see Table 1) and the rainfall amount during the Meiyu/Baiu season are investigated. The results are summarized in Tables 3a and 3b. As shown in Table 1, Meiyu seasons are included in the Baiu season from 1971 to 1984. So, in fact, the number of BAs of every type in Table 3a are taken during the Baiu season. The 90 % (95 %) Confidence level based on a two-tailed test corresponds to a correlation coefficient of 0.46 (0.53) in absolute value.

It is noteworthy that the number of persistent days of the Baiu season in Japan has a significant correlation with the total number of persistent days of Type B, both in the Baiu season and that from June to July. Type B in June and July has a slightly smaller correlation coefficient (0.48) with the number of persistent days of the Baiu season in Japan than for Type B in the Baiu season (0.69). The total number of persistent days of the Meiyu season and the rainfall amount during the Meiyu season in Central China also have a significant correlation with both DBS and DBT in Type C. It is interesting that the correlation associated with Type C in June to July (0.62/0.60) is better than that in the Meiyu/Baiu season (0.54/0.50). However, none of

these parameters associated with the Baiu or the Meiyu has any significant correlation to the appearance of Type A systems.

As mentioned in 3.2, many BAs of Types B and C occur during the MBS. Thus we will examine some possible effects of BAs of Types B and C on the MB phenomena in the following part of the present study.

4.2 Influence of the situation of Type B BAs on the Baiu in Japan

Figures 4a and 4b are the composite maps of OLR for Type B and Type C, which coincided with Figs. 3b and 3c, respectively. Figure 5 shows the distribution of the average OLR for June to July, 1979–1984. The belt-shaped area with low OLR value (shaded area) in middle latitudes corresponds to the average position of the MB frontal zone. Also, the area with high OLR value south of the MB frontal zone corresponds to the average position of the subtropical high from June to July.

As shown in Fig. 4a, the belt-like area with low OLR for Type B is located from the Changjiang River (about 30°N/120°E) to the eastern part of Japan (about 35°N/140°E). The OLR distribution is similar to that in the climatological one presented in Fig. 5. It is noted that the value of OLR around the Japan Islands (about 33°N/130°E to about 36°N/140°E) in Type B is somewhat lower (216 Wm^{-2}) than that in June to July, 1979–1984 (220 Wm^{-2}), which suggests the more active situation of the Baiu front there in Type B than the mean one from June to July. As mentioned in Section 3.3, the Type B corresponds to the situation in which the Baiu trough exists. Under this circumstance, the southward intrusion of cold air or an upper-level

Fig. 4. The composite maps of OLR (Wm^{-2}) under the circumstance of BA in Type B (a) and in Type C (b) for the same time as in Figs. 3b and 3c, respectively. The contour interval is 4 Wm^{-2} . The shaded area indicates that the value is less than 220 Wm^{-2} .

cut-off low from a higher latitude can affect rainfall activity in the Baiu frontal zone around Japan (Ninomiya and Muraki, 1986; Ninomiya, 1989). This may be one of the reasons why a BA of Type B has a closer relationship to the number of persistent days of the Baiu, as shown in Table 3. However, further discussion of the influences of the BAs of Type B will not be made in the Present study.

4.3 Influence of the situation Type C BAs on the Meiyu in Central China

As found in Fig. 4b, the Baiu frontal zone identified by the low OLR area is located to the south of the Japan Islands ($30^\circ\text{N}/130^\circ\text{E}$ to $35^\circ\text{N}/150^\circ\text{E}$), although the value of OLR in the frontal zone is lower (active) than the average OLR field through June to

July. This will be discussed in Section 5.

It is also found from Figs. 4a and 4b that the Meiyu frontal zone around the Changjiang River Basin in Type C exists at the same position as the climatological one shown in Fig. 5, and the OLR is lower there than the averaged value from June to July, 1979–1984 (the active situation of the Meiyu front).

Figure 6 shows the relationship among the pentad-mean values of the southerly component of the wind at the 850 mb level (V_{850}) in South China (about 25°N), the anomaly of 500 mb level height (Z'_{500}) from the mean value for June to July, 1979–1983 in the area $60^\circ\text{--}70^\circ\text{N}/140^\circ\text{--}150^\circ\text{E}$ (about central part of Region C), and OLR in Central China (about 30°N) during June to July, 1979–1983. The data of

Fig. 5. Average OLR (Wm^{-2}) for the period of June to July, 1979-1984. The contour interval is 4 Wm^{-2} . The shaded area indicates that the value is less than 224 Wm^{-2} .

Fig. 6. Relationship among the pentad-mean V850 in South China, $Z'500$ in Region C, and OLR in Central China. Details are referred to in the text. Samples of the pentad-mean values for $\text{OLR} > 220 \text{ Wm}^{-2}$ are indicated by open circles and the others are indicated by black circles.

V850 were extracted from the Daily Weather Maps, JMA, at 1200 GMT for the stations 57993 (Kanchow, $28^{\circ}50'N/114^{\circ}50'E$), 59096 (Lienping, $24^{\circ}19'N/114^{\circ}30'E$) and 45004 (Hong Kong, $22^{\circ}19'N/114^{\circ}10'E$). OLR data at every $2.5^{\circ} \times 2.5^{\circ}$ latitude/Longitude grid point were averaged for the domain of $27.5^{\circ}\text{--}32.5^{\circ}N/110^{\circ}\text{--}120^{\circ}E$. These pentad mean data are for the same period as in Fig. 16 of Kato (1989)². The samples of the pentad-mean values for $\text{OLR} > 220 \text{ Wm}^{-2}$ are indicated by open circles and the others are indicated by black circles.

²Dr. Kuranoshin Kato, Water Research Institute of Nagoya University presented Fig. 16 of Kato (1989) by calculating the pentad-mean data of V850 around South China and those of OLR around Central China from the original data mentioned in the text. The present study used these calculated values provided by him.

As pointed out by Kato (1989), the lower value of OLR in Central China ($\leq 220 \text{ Wm}^{-2}$) (the active phase of the Meiyu front there) tends to appear primarily when the low-level southerly wind component is strong in South China. According to the present study, the total number of pentads when OLR in Central China is less than 220 Wm^{-2} (active Meiyu front there) for the situation of V850 in South China $\geq 3.0 \text{ ms}^{-1}$ and $Z'500$ around Region C $\geq +30 \text{ gpm}$ was 10, and for V850 $\geq 3.0 \text{ ms}^{-1}$ and $Z'500 < +30 \text{ gpm}$ was 10 also. The total number of pentads when OLR in Central China $> 220 \text{ Wm}^{-2}$ (inactive) are 4 and 12, respectively. Thus the appearance frequency of the pentads with lower OLR to the total pentads was 71 % when $\text{V850} \geq 3.0 \text{ ms}^{-1}$ and $Z'500 \geq +30 \text{ gpm}$, and was 45 % when $\text{V850} \geq$

Fig. 7. Relationship among $T'850$ in the northern area adjacent to the Meiyu frontal zone, $Z'500$ in Region C, $V850$ in South China, and OLR in Central China. Details are referred to in the text. Black circles and open circles indicate the same situations as in Fig. 6 and ones with a bigger circle attached indicate the condition of $V850$ not being less than 3 ms^{-1} .

3.0 ms^{-1} and $Z'500 < +30 \text{ gpm}$. Thus not only a strong low-level southerly wind in south China but also a high anomaly of the 500 mb-level height in Region C is favorable for an active phase of the Meiyu front in Central China.

Figure 7 shows the relationship among the pentad-mean values of the 850 mb-level temperature anomaly from the time mean from June to July ($T'850$) in the area $32.5\text{--}35^\circ\text{N}/112.5\text{--}117.5^\circ\text{E}$ (representing the northern area adjacent to the Meiyu-frontal zone), $Z'500$ in Region C, $V850$ in South China, and OLR in Central China (averaged for the same regions as in Fig. 6, respectively during June to July, 1979–1983. $T'850$ is based on the NMC data, as mentioned in Section 2. Black circles and open circles indicate the same situations as in Fig. 6 and those with bigger circles attached indicate the condition of $V850 \geq 3 \text{ ms}^{-1}$ in South China. Figure 7 is divided into quadrants I, II, III and IV by the lines for $T'850 = 0^\circ\text{K}$ and $Z'500 = 30 \text{ gpm}$. Table 4 shows the occurrence frequency ratios for $\text{OLR} \leq 220 \text{ Wm}^{-2}$ in each quadrant.

The ratio of Pentads with low OLR in Quadrant II (negative $T'850$ and high $Z'500$) shows a maximum (70%). Of the cases when $Z'500 \geq 30 \text{ gpm}$ around Region C, the Meiyu front tends to be more active when cold air ($T'850 \leq 0^\circ\text{K}$) exists just to the north of the front than in the case for $T'850 > 0^\circ\text{K}$. Furthermore, the cases when $V850 \geq 3 \text{ ms}^{-1}$ in South China total 5 pentads, which comprises 5/7 of the cases in which the OLR is lower than 220 Wm^{-2} in Central China for Quadrant II.

The composite maps of $Z500$ for the samples in Quadrants I and II of Fig. 7 are shown in Figs. 8a and 8b, respectively. The situations of the two composite maps at the 500 mb level are quite differ-

Table 4. Number of the samples for every quadrant in Fig. 7 and the occurrence ratio of $\text{OLR} \leq 220 \text{ Wm}^{-2}$ for every quadrant.

Qua. \ OLR	$\leq 220 \text{ Wm}^{-2}$	$> 220 \text{ Wm}^{-2}$	Ratio
I	5	6	45 %
II	7	3	70 %
III	9	11	45 %
IV	3	12	20 %

ent, though blocking-like ridges exist in Region C in both figures. A trough around Lake Baikal and a ridge around 80°E are identified in Fig. 8b ($Z'500 \geq 30 \text{ gpm}$ and $T'850 \leq 0^\circ\text{K}$) which represents the Type C shown in Fig. 3c. However, such features are not found in Fig. 8a ($Z'500 \geq 30 \text{ gpm}$ but $T'850 > 0^\circ\text{K}$). It is obvious that the ridge in Region C extends too widely in the zonal direction when $Z'500 \geq 30 \text{ gpm}$ but $T'850 > 0^\circ\text{K}$. It is suggested that the situation of Type C seems to be one of the most favorable conditions for a Meiyu front trough with the existence of cold air to the north of the front in association with the trough around Lake Baikal. In Section 6, a detailed case study will be made of this speculation.

5. Influence of Type C situation on the Baiu front around Japan

5.1 Correlation between OLR around Japan and $Z500$ field

As mentioned in 4.3, the Baiu front (identified by the low OLR area) around Japan is located in the southern region (Fig. 4b) compared to that in the normal year (Fig. 5). Figure 9 shows the one-point correlation map between pentad-mean values

Fig. 8. Composite Z500 distribution (gpm) for the samples in Quadrant I (a) and Quadrant II (b).

of OLR at a key point of 30°N/150°E and the 500 mb level height in June, 1979–1984³. The point 30°N/150°E is situated around the southern boundary of the Baiu frontal zone extending from west to east in the normal year. Thus the value of OLR there would be reflected by the north-south fluctuation of location of the front. The thresholds of the correlation coefficient at the 90 % and 95 % confidence intervals are 0.28 and 0.33, respectively.

The significant positive correlation areas are found in the Caspian Sea, as well as the area east of Honshu, Japan. To the north and to the south

³In order to check the sensitivity of results, the correlations between the 500 mb height in the area 20–80°N and 20–180°E and the OLR at points around MB frontal zone (27.5–40°N/110–160°E) were all computed.

of Japan, areas with significant negative correlation are located, which correspond to the BA around the Okhotsk Sea and the sub-tropical anticyclone, respectively. It is seen that areas with a relatively large magnitude of correlation coefficient arrange along a great circle from the Caspian sea to the sea area southeast of Japan through Lake Baikal (marked by letters A-F in this figure). This pattern might be suggested to be the ray path of a stationary Rossby wave train from the point A to F as proposed by Hoskins and Karoly (1981). However, the group of centers with correlation over the 90 % confidence level from the Okhotsk Sea (the point D) to the tropics (F) is separate from another group (A). It is noted that the point D corresponds to Region C. Although the wave train-like pattern reaches

Fig. 9. Distribution of correlation coefficients between OLR at a key point ($30^{\circ}\text{N}/150^{\circ}\text{E}$) and the 500 mb-level height at points of the area in June, 1979–1984. Shaded areas show the values over the absolute value 0.3 (over the 90 % confidence level) and the thick line (A–F) links the positive and negative anomaly centers.

Fig. 10. Composite map of pentad 500 mb height in June (gpm), 1979–1984, extracted when the OLR in the same pentads are lower than 215 Wm^{-2} (a) and when the pentad OLR are higher than 240 Wm^{-2} (b). Each value is a deviation from the time mean. The contour interval is 5 gpm, with negative ones dashed.

Fig. 11. Composite map of pentad OLR in June (Wm^{-2}), 1979–1984, extracted when the pentad OLR are lower than 215 Wm^{-2} (a) and when the pentad OLR are larger than 240 Wm^{-2} (b). Each value is a deviation from the time mean. The contour interval is 8 Wm^{-2} , with negative ones dashed. Shaded areas indicate the part of the absolute value over 32 Wm^{-2} .

the region to the south of Japan, it is a different pattern from that which originates from the tropical western Pacific mentioned by Tsuyuki and Kurihara (1989).

Figure 10a presents the composite distribution of anomaly of height at the 500 mb level ($Z'500$) for the pentads when the time mean OLR at $30^\circ\text{N}/150^\circ\text{E}$ was lower than 215 Wm^{-2} and Fig. 10b for the pentads when the OLR was higher than 240 Wm^{-2} ⁴. Figures 11a and 11b are the distributions of composite OLR anomaly for the same pentads as in Figs. 10a and 10b, respectively. In this section the anomalies are calculated as the deviations from mean val-

ues in June, since correlation patterns in July are rather different from those in June, as will be mentioned later.

Positive anomaly centers of $Z'500$ exist at $60^\circ\text{N}/80^\circ\text{E}$ and near the Okhotsk Sea, and negative centers exist in the Caspian Sea, Lake Baikal and the sea east of Japan when OLR at $30^\circ\text{N}/150^\circ\text{E}$ is low (Fig. 10a), corresponding to those with peaks of correlation coefficient in Fig. 9. When OLR at $30^\circ\text{N}/150^\circ\text{E}$ is high (Fig. 10b), the magnitude of the negative anomaly (-10 gpm) around the Okhotsk Sea (the point D) is rather smaller than that in Fig. 10a ($+25 \text{ gpm}$). It is suggested that the large negative situation of OLR at $30^\circ\text{N}/150^\circ\text{E}$ corresponds to the Type C situation (Fig. 10a). As for the OLR

⁴Although the figure is not shown here, the mean OLR at $30^\circ\text{N}/150^\circ\text{E}$ in June, 1979–1984 was 234 Wm^{-2} .

Fig. 12. Same as Fig. 9, but in July.

distribution, a long slender area of anomaly is found in the sea area to the southeast of Japan. This corresponds to the southward shift of the Baiu front there from the climatological position (not shown) in June. However, the magnitude of the composite OLR anomaly is not generally as large, except for the area mentioned above. In other words, a large negative anomaly of OLR at about $30^{\circ}\text{N}/130^{\circ}\text{--}160^{\circ}\text{E}$ appears with the wave train-like anomaly of Z500 from the point A to E in Fig. 9. Although the magnitude of Z'500 around B and C is not so small despite the weak correlation, it is especially large around the Okhotsk Sea (the point D) and the point E (about $35^{\circ}\text{N}/150^{\circ}\text{E}$) for this situation. It is also noted that there is not the position shift of the Meiyu front as shown in Figs. 10a (a small negative deviation of OLR is located in Central China where the Meiyu front exists).

The correlation fields of the 500 mb height anomaly to the OLR at the key point ($30^{\circ}\text{N}/150^{\circ}\text{E}$), in July is shown in Fig. 12. Although significant positive areas are still found to the east of north Japan and the Caspian Sea, the sub-tropical areas are covered completely by negative correlation, and there is not the wave train-like pattern from high latitudes to the tropics as shown in June.

5.2 A Case Study for June 1982

In order to investigate the relationship between the Type C situation and the behavior of the Baiu front further, a case study was carried out for June 1982, when a BA in Region C persisted for a long time (during the last 10-day of June). Figures 13a, 13b, and 13c show the mean fields of geopotential height at the 500 mb level during 15–19, 20–24, and 25–29 June (which are referred to as Pentads 34, 35 and 36, respectively) in 1982. The BA developed and persisted around the Okhotsk Sea area in Pentads 35 and 36. The BA in Pentad 36 moved about 1000 Km westward from that of Pentad 35. The ridges around 80°E and the Okhotsk Sea were

located at the climatological position of positive anomaly centers of Z'500 and the troughs around Lake Baikal and to the east of Japan near the negative anomaly centers in Fig. 10a. Thus a similar wave train-like pattern to that in Fig. 10a is found also in this case.

Figure 14 shows time evolution of twice-daily 500 mb height deviation from the zonal mean along the great circle A–F in Fig. 9 during 15–29 June, 1982. There are some large positive and negative anomaly centers arranging closely in Fig. 14. A wave train-like propagation from $50^{\circ}\text{N}/80^{\circ}\text{E}$ (the point B) to lower latitudes around $37.5^{\circ}\text{N}/150^{\circ}\text{E}$ (the point E) along the great circle is found from 20 to 23 June, as subjectively indicated by the thick line. This suggests that the wave train-like propagation did not originate around the Caspian Sea area ($40^{\circ}\text{N}/50^{\circ}\text{E}$), but from a region further downstream. The other wave train-like propagation originated around the Okhotsk Sea (the point D) and headed to the tropics along the great circle and is also seen from 26 to 28 June. In the latter case, the influence from the upstream region of the Okhotsk Sea is not seen. These facts suggest that the wave train-like propagation originated from a region near the Okhotsk Sea or was amplified there. When the two Rossby wave propagations occurred, the positions of the 5800 mb contour line to the south of Japan in Pentads 35 and 36 existed more southward than that in Pentad 34 (not shown here). This means that the Sub-tropical High there became weak then. The speed of propagation is estimated to be about 15 m/s, which coincides with the speed of the propagation from the tropics to higher latitudes during the summer season (Kurihara and Tsuyuki, 1987).

Figures 15a and 15b show the time-latitude section of twice-daily OLR during 15–25 June, 1982 for mean values from 110°E to 120°E and from 130°E to 150°E , respectively. It was found that, when the propagation reached the point E on 22 June in Fig.

Fig. 13. Spatial distribution of pentad 500 mb height (gpm) for the period of June 15–19 (a), 20–24 (b) and 25–29 (c), 1982. The contour interval of the 500 mb height (thin lines) is 40 gpm. The thick lines indicate a trough.

14, the eastern part of the low OLR area (about 130–150°E in Fig. 15b) moved southward, keeping its intensity. In this case, the western part of the low

OLR are (about 110–120°E in Fig. 15a) also moved southward to about 25°N on 21 June and became weak. However, it was suggested to be associated

Fig. 14. Time evolution of the twice-daily 500 mb height deviations (gpm) along the great circle A-F in Fig. 9 for the period of June 15-29 1982. Each value is a deviation from the daily zonal mean. The contour interval is 20 gpm, with negative ones dashed. Thick solid lines are subjectively defined courses of wave propagations.

with the intrusion of cold air along about 115°E and not to be due to the propagation of the wave, as will be mentioned in Section 6.

5.3 Discussion

In Subsection 5.2, the Rossby wave train-like propagation might originate from the Okhotsk Sea area or be amplified there. Okawa (1973) pointed out that the thermal contrast between the continental area of East Siberia and the Bering Sea is very much larger in early summer. The Rossby wave is excited generally, depending on the topographic forcing and distribution of heterogeneous heating, if excluding the internal variability of the atmosphere itself (Huang, 1990). Thus the large thermal contrast and suddenly raising of the temperature by warm-temperature advection moving from the west of East Siberia might be thought as one of the possible factors for driving the Rossby wave propagation. The finding is obviously different from the Rossby wave propagation from the north of the Philippines to high latitudes in summer, discussed by Kurihara and Tsuyuki (1987), Nitta (1987), and Tsuyuki and Kurihara (1989). It will be necessary to study the Rossby wave propagation in the future using theoretical and numerical models.

Secondly, as mentioned in Section 5.1, the one-

point correlation map in June (Fig. 9) shows a very different pattern from that in July (Fig. 12). According to Tsuyuki and Kurihara (1989), the Rossby wave propagations from the tropics (near the Philippines) to high latitudes often occur in summer, including July. This propagation may disturb the Rossby wave propagation from high latitudes to the tropics, which might be a possible reason why the pattern in Fig. 12 is different from the pattern in Fig. 9. This will not be discussed in the present study in detail. JMA (1971) pointed out the importance of Okhotsk High (related to the BA in Type C in the present study) to the large-scale circulation at the 500 mb level in the Baiu season.

As will be seen in Section 6, there persisted also the high at the 1000 mb level (Okhotsk high, surface level). In such situations a cold air outbreak with a thickness of only about 1 Km from the sea surface occurs along the eastern edge of the Japan Islands (Kudo, 1984; Ninomiya and Mizuno, 1985a, b). However, the cold air is warmed by the heat supplied from the sea when it reaches in the Kuroshio (the warm sea current) region around 30-35°N. The present study proposed the possibility of an effect of Rossby wave propagation from the Okhotsk Sea area on the southward movement of the Baiu front (130-160°E) in the situation of Type C, although

Fig. 15. Time-latitude section of twice-daily OLR (Wm^{-2}) during 15–25 June, 1982 for mean values from 110°E to 120°E (a) and from 130°E to 150°E (b). Shaded areas are less than 210 Wm^{-2} .

the forcing or enhancement process of the wave around the Okhotsk Sea is a remaining problem.

6. Cold air intrusion (A case study for June 1982)

As mentioned in Section 4.3, the Meiyu front in Central China tends to be active with relatively cold air in the lower layer just to the north of the front in the situation of Type C. In this section, a detailed description of the intrusion of cold air in this situation is made for a case in June 1982. Figure 16 shows the temporal changes of the contour line of Z500 for 5700 gpm and the center of low pressure depression at sea surface level at 1200 GMT from

17 June to 21 June, 1982. The positions and center pressure of the depression are based on the Daily Weather Charts issued by the JMA, and the 500 mb-level contours are based on NMC data.

The trough around $60^{\circ}\text{N}/90^{\circ}\text{E}$ deepened and moved eastward gradually on 17 June. The 5700 gpm contour near the trough was identified around Lake Baikal. With the development of the trough, the 5700 gpm contour line was shifted southward to about $44^{\circ}\text{N}/100^{\circ}\text{E}$ (to north of Tibet Plateau) and a cyclone at sea surface level was formed about $48^{\circ}\text{N}/112^{\circ}\text{E}$ on 19 June. The trough axis tilted westward with height and the system showed the structure of baroclinic waves. The southern edge of

Fig. 16. Temporal changes of the contour line of Z500 for 5700 gpm and the position and value of low pressure depressions at sea surface level from 17 June to 21 June, 1982. The digits 17 to 21 are 17 June to 21 June and the digits in brackets are the value of low pressure depression (mb).

the 5700 gpm contour reached about 40°N/120°E on 21 as this disturbance moved eastward. On the other hand, the cyclone at the sea surface level around 55–60°N/120–130°E moved little during 17–21 June and a BA around the Okhotsk Sea formed on 21 June. It is noted that the formation of a BA there was in association with the eastward movement of the baroclinic wave from about 90°E and the southward intrusion of the trough to North China.

Figures 17 and 18 show the sequence of twice-daily temperature anomaly distributions at the 500 mb and 850 mb levels, respectively, based on the NMC data. The anomalies are calculated as the deviation from the 10-day mean fields during 16–25 June, 1982. Figure 19 shows the 1000 mb-level height field with locations of the front at sea surface level for that period. The 1000 mb-level height is based on the NMC data and the front is based on the Daily Weather Charts issued by JMA.

Accompanied by the establishment of the quasi-stationary trough at the 500 mb level extending from 65°N/115°E to 40°N/102.5°E (20–24, June in Fig. 13b), the cold air area (temperature anomaly of -4 to -6°K) at the 850 mb level reached the Changjiang River Basin (around 30°N) on 22 June. The intrusion of cold air there around 22 June is confined to the lower level (compare to Fig. 18). On 24 June, the cold air at the 500 mb level reached the region. On 20 June, the strong cold front originating from the low center at 55°N/122°E to 37°N/110°E associated with the baroclinic wave mentioned just before moved southeastward, reaching 32°N/122°E (Central China) on 21 June as shown in Fig. 19. The cold air reached near 30°N at 850 mb by then.

At that time, the cyclone along the MB front was formed and moved eastward (30°N/110–130°E in Fig. 19) and OLR around Central China became very low, as shown in Fig. 15a. After that time, the low OLR area moved eastward as movement of the cyclone at about 30°N. We should note that the cold air intrusion in the lower layer along the Tibetan Plateau looks like the cold surge toward Central and South China in winter, as pointed out by Murakami (1981) and Murakami and Nakamura (1983), although the major cyclone at about 50°N did not move further eastward in association with the location of blocking ridge in Region C.

Takahashi (1989, 1991) pointed out the importance of the area with low temperature on or just north of the Meiyu precipitation zone in Central China or just to its north. He also classified the formation processes of the low-temperature area into types. The case in this section seems to correspond to the Type E in Takahashi (1991), in which the cold air migrates southward around 110°E between the quasi-stationary trough (around 125°E) and a ridge (around 90°E) system at the 500 mb level. The present study suggests that such a situation tends to occur in association with the persistence of a BA around 140°E (Region C).

The present study has shown the significant correlations between Type C and the Meiyu rainfall amount/Meiyu period in Section 4, and pointed out the lower OLR around Central China occurring with high frequency under the circumstance of combination of larger V850 in South China with higher Z'500 in Region C. Why the Type C has a close relationship to the Meiyu front needs to be analyzed fur-

Fig. 17. The sequence of 500 mb temperature anomaly distribution (K). Each panel represents an anomaly distribution for a 10-day mean field (from 16–25 June, 1982). Shading indicates the negative anomaly areas smaller than 4K from the 10-day mean field.

Fig. 18. Same as Fig. 17, but for the 850 mb temperature distribution (K).

Fig. 19. The 1000 mb-level height field (gpm, thin lines) with fronts (thick lines) at sea surface level during 16-25 June.

ther. But it can be said, at least, that a development of a BA in Region C is one of the important factors for the cold air coming southward, which results in a favorable situation for the active phase of the Meiyu, combined with strong southerly wind in South China.

7. Summary and Conclusions

Distribution of BAs in Eurasia during the Meiyu/Baiu season and some possible influences of BAs on the behavior of the MB frontal zone were examined through statistical analyses. Then detailed analyses were made for a case in late June 1982.

The following results were obtained:

(1) High appearance frequency of the BAs was observed in three regions: 31–60°E, 91–110°E and 131–150°E of the middle and high latitudes of the Eurasian continent. The maximum occurrence frequency of BAs is seen in the region of 131–150°E. It is noted that the BAs in Regions B and C tends to appear more frequently in the Baiu season than that in the non-Baiu season from June to July.

(2) The BAs in Region A (21–80°E) have little relation to the number of persistent days of the Meiyu/Baiu period and the total precipitation during that period in East Asia. BAs in Region B (81–120°E) showed the positive correlation with the number of persistent days of the Baiu period in Japan, in which the Baiu trough, as pointed out by Ninomiya and Muraki (1986) and Ninomiya (1989), is located to the east of the BA in Region B.

(3) BAs in Region C (121–160°E), referred to as Type C, have a positive correlation with both the number of persistent days of the Meiyu period and the Meiyu rainfall in China. The zonal scale of BAs in Region C in the zonal direction is somewhat smaller than those in other regions, and a trough is found around 110°E. The statistical analysis using the 5-day mean values suggests that the cold air in the lower layer in 32.5–35°N/112.5–117.5°E (just to the north of the Meiyu front) in Type C is an important factor to activate the Meiyu front in Central China, together with the enhancement of the low-level southerly wind component in South China.

(4) A case study in late June of 1982 revealed that cold air intrusion toward Central China in the situation of Type C occurred mainly in the lower layer, and was accompanied by the development of a baroclinic instability wave around 50°N/100–110°E. Time evolution of the southward shift of cold air was somewhat similar to the cold surge in winter, as mentioned by Murakami (1981) and Murakami and Nakamura (1983). It is interesting that the formation of the Type C situation was a favorable condition for cold air coming southward to the Meiyu frontal zone.

(5) The stationary Rossby wave train-like pattern

in the anomaly field of Z500 from the Okhotsk Sea area to the tropics through east of Japan in June is found. Although the process of its forcing could not be discussed in this paper, the amplitude of the wave was increased largely from Lake Baikal to the Okhotsk Sea area, as shown by the case in June 1982. The propagation caused a negative anomaly of the 500 mb-level height to the areas east of Japan, with the development of a BA around the Okhotsk Sea. OLR in the Baiu front around Japan then decreased (activated), but the Baiu front shifted southward with a weakening of the sub-tropical high in nearby regions. The present study suggests that the climatological features of the Meiyu front in China are influenced quite differently from those around Japan by the Type C situation.

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ユーラシアのブロッキング高気圧の華中や日本の梅雨に対する影響

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梅雨期におけるユーラシア大陸の中・高緯度に出現するブロッキング高気圧の出現特性とこれらの梅雨前線に対する影響について統計解析を行った。さらに、1982年6月の後半についての事例解析も行った。

50–70°N/21–160°Eの範囲内でみると、ブロッキング高気圧は31–60°E、91–110°E、131–150°Eの3つの地域に多く出現する。最も頻度が集中しているのは131–150°Eで、91–110°Eの地域が第2番目に卓越する。

梅雨期におけるB地域(50–70°N/81–120°E)でのブロッキング高気圧の継続日数は、日本の梅雨期の日数(number of persistent days of Baiu)と正の相関がある。一方、梅雨期におけるC地域(50–70°N/121–160°E)でのブロッキング高気圧の継続日数は、華中の梅雨期の日数(number of persistent days of Meiyu)及び梅雨期の降水量(rainfall of Meiyu)と正の相関がある。

統計解析の結果によると、Meiyu前線のすぐ北方における対流圏下層の寒気域の存在は華南における下層南風の増加とともにMeiyu frontを活発化させる重要なfactorであるが、C地域のブロッキング高気圧の存

在は、華中の前線帯のすぐ北方への寒気侵入時にみられる1つの代表的なパターンであることが分かった。更に、1982年6月の事例解析によると、C地域のブロッキング高気圧の発達はその後面の $50^{\circ}\text{N}/100\text{--}110^{\circ}\text{E}$ 付近の傾圧不安定波の発達と平行して起こり、この低気圧の寒冷前線の南下に伴って華中の前線帯へ下層寒気が南下した。つまり、C地域でのブロッキング高気圧発達過程において下層寒気の南下も見られたことになる。

一方、6月のオホーツク海、日本東部の太平洋上を経て熱帯地域へ至る波列 (wave train) が解析された。この現象はC地域のブロッキング高気圧の発達とともにロスビー波の伝播によって生じたものと考えられる。その forcing processes はまだ明らかではないが、1982年6月の後半の事例解析は、波がバイカル湖からオホーツク海にかけて増幅されたことを示唆している。この波の伝播により、日本以東の海洋上に負の高度偏差がもたらされ、梅雨前線は南に移動したことが示唆された。本論文の結果は Meiyu front と Baiu front の気候学様相に対し、C地域のブロッキング高気圧が異なる影響を及ぼすことを示唆している。