Diurnal Variation of Cb-Clusters over China and Its Relation to Large-Scale Conditions in the Summer of 1979

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(Manuscript received 11 April 1995, in revised form 30 September 1995)

Abstract

The appearance frequency of Cb-clusters and its diurnal variation were examined in relation to large-scale conditions based on the observational data from June to August 1979. The analysis was applied to the three stages in the seasonal march in that year, i.e., “Pre-Meiyu” (1-17 June), “Meiyu” (20 June-22 July) and “Mid-summer” (23 July-17 August). The main results are as follows.

(1) The Cb-clusters appeared frequently not only in the Baiu frontal zone but also in North to Northeast China (Area N1) in “Meiyu”, and in Central China (Area C2) in “Mid-summer”. A remarkable diurnal variation of appearance frequency of the Cb-clusters with an evening maximum was observed in Area N1 in “Meiyu” and Area C2 in “Mid-summer”. The daily maximum of ground surface temperature in these two cases was very high.

(2) In Area N1 in “Meiyu”, the Cb-clusters with diurnal variation were mainly embedded in large-scale cloud systems corresponding to slow-moving upper-level lows or troughs. The specific humidity in the lower layer increased from “Pre-Meiyu” to “Meiyu”. These two factors, as well as the strong surface heating, would provide a favorable condition for the frequent appearance of Cb-clusters due to the increase of convective instability. The large-scale horizontal convergence in the lower layer was stronger at 12 UTC (20 BST) than at 00 UTC (08 BST), which would lead to the development of Cb-clusters in the evening.

(3) Area C2 was covered by the subtropical high, and the low-level divergence was generally stronger at 12 UTC than at 00 UTC. In spite of these conditions, the isolated Cb-clusters developed very frequently in the evening. The very strong surface heating in the daytime could contribute to release of the strong convective instability by generating meso-scale upward motion as a trigger.

1. Introduction

Over the continental part of China, regions with different land surface and atmospheric conditions are located very close to each other, such as the subtropical humid climatic region from Central China to South China (~35-23°N/110-120°E), and the arid or semi-arid regions from Takla Makan to North China (~40-50°N/70-125°E). These regions would be favorable test fields for the study by intercom-
acterized by a large meridional gradient of specific humidity (Akiyama, 1973; Ninomiya, 1984; Saito, 1966). Heavy rainfall events also occur, very often accompanied by organized meso-α or β-scale (Fujita, 1981) deep convective clouds (Akiyama, 1973, 1984a, b, 1989, 1990a, b; Ninomiya, 1984, 1989; Ninomiya and Akiyama, 1992; Ninomiya and Mizuno, 1987). On the other hand, many deep convective clouds in such a horizontal scale also appear to the north of the Baiu frontal zone in China where the time-averaged cloud amount is rather smaller than in the Baiu frontal zone, according to the statistical studies by Ninomiya (1989), Takeda and Iwasaki (1987) and Iwasaki and Takeda (1993). The meso-α-scale convective clouds show multiscale structures in which meso-β or γ-scale clouds are embedded, and are considered as significant weather systems (Akiyama, 1984a, b; Madox, 1980, 1983; McAnelly and Cotton, 1986; Ninomiya et al., 1981, 1988a, b). In the present study we simply refer to such meso-α-scale deep convective clouds (including larger meso-β-scale ones) as the Cb-clusters, although stratiform clouds might be sometimes embedded in them. It should be noted that the frequent appearance of the Cb-clusters does not always correspond to the large amount of rainfall or cloud amount for large-scale domain. Besides the role in large-scale diabatic heating, frequent appearance of the Cb-clusters would be reflected by the concentration of water vapor itself within the large-scale domain, even in a region without enough large-scale convergence of moisture. In other words, the appearance frequency of the Cb-clusters can be an indicator for describing cloud climatology and related large-scale processes, and it provides different information from rainfall and cloud amounts.

Takeda and Iwasaki (1987) and Iwasaki and Takeda (1993) also pointed out that the appearance frequency of the Cb-clusters tend to be subject to remarkable diurnal variation with the maximum from afternoon to evening over China, especially to the north of ~35°N. This implies that the diurnal variation of the heating from the ground is also an important factor for the water cycle there.

It should be noted that the location and the characteristics of the Baiu frontal zone in East Asia present several step-wise seasonal transitions from spring to summer (Ding, 1992; Hirasawa et al., 1995; Kato, 1985a, 1987, 1989; Kato and Kodama, 1992; Ninomiya, 1989; Ninomiya and Muraki, 1986). The large-scale atmospheric conditions associated with appearance of the Cb-clusters would be rather different, not only with respect to the location relative to the Baiu frontal zone but also with respect to the stage of this seasonal march. However, the statistics by Takeda and Iwasaki (1987) and Iwasaki and Takeda (1993) were made for the periods including different stages in the seasonal transition.

Many studies on the large-scale features of the Baiu frontal zone and their seasonal transitions in 1979 have been made (Kato, 1985a, 1987, 1989; Kato and Kodama, 1992; Ninomiya, 1989; Ninomiya and Muraki, 1986). Thus the present study will firstly describe the appearance frequency of the meso-α-scale Cb-clusters (including large meso-β-scale ones) with diurnal variation over China from

Fig. 1. Time-latitude sections of 5-day mean Q850 (g kg⁻¹) and T850 (°C) averaged from 110°E to 120°E are shown in (a) and (b), respectively. The areas surrounded by broken lines indicate that meridional gradient of θₑ (-½ φθₑ) at the 850 hPa level is greater than 15 K/1000 km, where a and φ are radius of the earth and latitude, respectively. Areas with Q850 larger than 12 g kg⁻¹ (in (a)) and those with T850 higher than 18°C (in (b)) are shaded.
June to August 1979. Then we will investigate large-scale atmospheric and land surface conditions. We will focus our attention on the regions adjacent to the Baiu frontal zone (i.e., North China and Northeast China from late June to early July, and Central China from late July to early August).

2. Data and analysis method

2.1 Data sources

The following data in 1979 were mainly used in the present study.

(1) Monthly Surface Meteorological Data of China, published by the Climate Data Office of the National Meteorological Center, State Meteorological Administration of China. The data at about 180 synoptic weather stations are available for the entire region of China (hereafter this data book is referred to as SYCH). The present study used a part of these data in the magnetic tape edited by Masuda et al. (1991).

(2) The twice-daily objective analysis data at the grid points on the polar stereo projection map (381 km x 381 km at 60°N) interpolated by the operational Northern Hemisphere Objective Analysis System of the Numerical Prediction Division of the Japan Meteorological Agency (JMA) (referred to as ANLMON).

(3) The infrared GMS imageries for the East Asian region in the form of microfilm images every 6 hours (00, 06, 12 and 18 UTC).

2.2 Method for identification of the Cb-clusters

In the present study, a Cb-cluster was manually identified from the GMS infrared imagery on microfilm as satisfying the following three criteria simultaneously, after Takeda and Iwasaki (1987) and Iwasaki and Takeda (1993):

(a) The oval-shaped cloud mass region where \( T_{BB} \) is lower than \(-50^\circ C\), to be more than 100 km in diameter.

(b) The horizontal gradient of \( T_{BB} \) to be large near the rim of the cloud mass (at least a part of the rim).

(c) It is to be formed in the region to the north of 20°N. Cloud systems such as tropical disturbances are not included.

The region with \( T_{BB} \) value lower than \(-50^\circ C\) can be roughly identified, referring to the grey-scale attached to each imagery. The location of a Cb-cluster was defined as its geometric center. Examples of the Cb-clusters identified by the above criteria are referred to Fig. 1 of Iwasaki and Takeda (1993). According to the temporal GMS infrared imageries, a cloud mass associated with deep convection is often isolated and has a large \( T_{BB} \) gradient around its rim (possibly reflected by a meso-scale compensating downdraft in its just outer region), even if it is embedded in a large-scale cloud system. A cloud mass extracted from the criteria (a) and (b) can be regarded as such a cloud system. However, it is rather difficult to select a simple threshold value of \( T_{BB} \) gradient around its rim for following reasons:

(1) some ambiguity of grey-scale of the microfilms,

(2) the variation of the air temperature around the tropopause level with respect to latitude,

(3) difference of the stage in its life cycle, and so on.

Although it is necessary to extract Cb-clusters with more objective “calculations” in the future, visual methods remain a very effective way for identification of the isolated Cb-clusters.

3. Seasonal change in location of the frontal zones around China

Figures 1a and 1b show the time-latitude sections of 5-day mean specific humidity and air tempera-
Lure at the 850 hPa level (Q850 and T850, respectively) averaged over 110°E–120°E in the warm season of 1979, based on ANLMON. The areas where the meridional gradient of equivalent potential temperature $\theta_e$ at the 850 hPa level is greater than 15 K/1000 km are also presented by broken lines.

The Baiu frontal zone in China, as identified by large gradients of Q850 and $\theta_e$, moved northward to Central China ($\sim$30°N) on $\sim$20 June. It

Fig. 3. Distributions of the Cb-clusters in “Meiyu” and “Mid-summer”. The distributions from midnight to morning (18 UTC and 00 UTC) and those from afternoon to the evening (06 UTC and 12 UTC) are shown.
moved further northward to North China (~40°N) on ~23 July (the dates were determined also referring to the daily fields). The period from 20 June to 22 July is the “Meiyu” season in Central China and the mature stage of the “Baiu” season in the Japan Islands. The period of 23 July-17 August corresponds to a mid-summer season there (Kato, 1989; Ninomiya and Muraki, 1986; Ninomiya, 1989; Matsumoto, 1985). Hereafter, we will refer to the period from 20 June to 22 July 1979 as “Meiyu” and that from 23 July to 17 August 1979 as “Mid-summer”. For comparison, some features for a period from 1 to 17 June 1979 were examined (this period is referred to as “Pre-Meiyu”). Note that “Pre-Meiyu” corresponds to the stage after the abrupt disappearance of the low-level temperature gradient across the Baiu frontal zone in South China (Kato, 1985, 1987).

Figures 2a and 2b show the distributions of $\theta_e$ at the 850 hPa level averaged in “Meiyu” and “Mid-summer”, respectively, together with the magnitude of the horizontal gradient ($\nabla \theta_e$). Contours only for $|\nabla \theta_e| > 10$ K/1000 km are shown by dotted lines. The area with large $|\nabla \theta_e|$ (e.g., more than 10 K/1000 km) is found around 33°N in China, corresponding to the Baiu frontal zone. The locations of these domains are also indicated in this figure. These regions for each period were selected referring to the relative locations from the Baiu frontal zone. Thus the boundary of the domains is slightly different between Areas C1 and C2, and rather different between Areas N1 and N2.

In “Meiyu”, Cb-clusters appear very frequently both in daytime and night time in the Baiu frontal zone in Central China (Area C1). However, we can find another region (Area N1) where the Cb-clusters appeared very frequently, although the time and areal-averaged rainfall amount is smaller than in Central China. It is noted that the appearance frequency in Area N1 exhibits a strong diurnal variation with a maximum at 12 UTC (20 BST). The value at 12 UTC in Area N1 in “Meiyu” is comparable to that in the Baiu frontal zone (Area C1 in “Meiyu”).

A similar diagram for Area N1 in “Pre-Meiyu” is presented in Fig. 5. The appearance frequency of the Cb-clusters is small, even in the evening in “Pre-Meiyu”. Thus its diurnal variation in Area
N1 became very clear after the northward shift of the Baiu frontal zone from South China to Central China around 18 June (see Fig. 1), although Area N1 was located to the north of the Baiu frontal zone in both “Meiyu” and “Pre-Meiyu”.

In “Mid-summer”, the Cb-clusters appear there frequently from afternoon to evening, although the time and areal-averaged rainfall amount in Central China (Area C2) is small. The appearance frequency shows remarkable diurnal variation with maximum at 12 UTC in Area C2 in “Mid-summer”. The amplitude of the diurnal variation is the largest in Area C2 in “Mid-summer”. The diurnal variation with maximum at 12 UTC is also found in Area N2.
N2. However, the total number of the Cb-clusters in Area N2 is not so large.

5. Ground surface temperature

Figure 6 shows the latitudinal distributions of daily maximum $T_g$ ($T_g$ max) and that of daily mean $T_g - T_a$, averaged for “Pre-Meiyu”, “Meiyu” and “Mid-summer” based on SYCH, where $T_g$ and $T_a$ denotes ground surface temperature and air temperature at the surface level, respectively. The ground surface temperature in the meteorological stations in China is measured by putting the thermometer on the ground, with the sensor touching the ground surface. One might wonder about the accuracy of the ground surface temperature observation. However, such measurements give reasonable values according to the field experiment by Saigusa et al. (1993), although it tends to underestimate slightly by about a few °C when $T_g$ is very high compared to $T_a$.

The daily maximum of ground surface temperature averaged for “Meiyu” exceeds 40°C in Area N1 (to the north of 40°N), and attains more than 50°C in Area C2 in “Mid-summer” (around 30°N). The daily mean $T_g - T_a$ is also larger in these regions (4.0 to 5.5°C) than in the Baiu frontal zone (around 30°N). In such regions, the sunshine duration averaged for the periods is 7 to 9 hours/day in most stations in Area N1 in “Meiyu” and 8 to 10 hours/day in Area C2 in “Mid-summer” (not shown here). It is rather longer than that in Area C1 in “Meiyu” (3.5 to 6 hours).

Thus it is suggested that the large sensible heat flux from the ground due to insolation contributes to the frequent appearance of the Cb-clusters with diurnal variation in Area N1 in “Meiyu” and Area C2 in “Mid-summer”. However, it is also noted that the appearance frequency of the Cb-clusters in Area N1 in “Pre-Meiyu” is not so large, although $T_g$ max and the daily mean $T_g - T_a$ are as large as in “Meiyu”. This suggests that the combined effects of the other factors with the daytime heating from the ground can provide climatological conditions favorable for the frequent appearance of the Cb-clusters with diurnal variation. In the following sections, we will examine the synoptic situations for the cases in Area N1 in “Meiyu” (just to the north of the Baiu frontal zone) and Area C2 in “Mid-summer” (in the subtropical high area).

6. Area N1 in “Meiyu” (between the Baiu frontal zone and the polar frontal zone)

6.1 Day-to-day variation of locations of Cb-clusters

Figure 7 shows the time-latitude section of geopotential height at the 500hPa level ($Z_{500}$) along 115°E, together with the latitudes of the Cb-clusters which appeared between 110°E and 124°E. The locations of the Cb-clusters are analyzed only for the region to the south of 50°N. The number of the Cb-clusters increased with a period of about 5 to 7 days around Area N1 (38°N–50°N) in “Meiyu”, i.e., around 21, 28 June, 3, 9, 13, and 19 July. Roughly speaking, the increase in the number of the Cb-clusters seems to correspond to the approach of a 500 hPa trough.

Table 1 presents the frequency of days when more than one Cb-cluster appeared at 12 UTC in the domain of 42–48°N/110–120°E (referred to as FCCB hereafter) for Phases A and C. In both cases, most of the Cb-clusters at 12 UTC were associated with diurnal variation. Phase C is a situation when a cyclonic vorticity at the 500 hPa level (upper-level trough or low) covers or is approaching the region. If the upper-level trough covers the area, the areal-mean relative vorticity at the 500 hPa level ($\nabla \cdot \nabla \cdot \text{VR}_{50}$, where a bar indicates the areal mean) would be positive. If the trough is just approaching the area, horizontal advection of relative vorticity at that level ($-\nabla \cdot \text{VR}_{50}$, referred to as HADV) would be positive. Thus a day is identified as Phase C, when a

<table>
<thead>
<tr>
<th>Phase</th>
<th>Frequency of days (%) when more than one Cb-cluster appeared at 12 UTC in the domain of 42–48°N/110–120°E (FCCB), for Phases A and C.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase A</td>
<td>20</td>
</tr>
<tr>
<td>Phase C</td>
<td>30</td>
</tr>
</tbody>
</table>
pair of values \((V_{R50}, HADV)\) lies above the straight line \(HADV = -V_{R50}\) in Fig. 8. Phase A is a situation when an anticyclonic vorticity covers the area or is just approaching it (the area below the line \(HADV = -V_{R50}\)). Since the location relative to the 500 hPa trough might be rather different within Area N1, FCCB is examined for the domain of 42–48°N/110–120°E with ANLMON.

FCCB exceeds 50 % in Phase C in “Meiyu”, while it attains about 30 % in Phase A. Recalling Fig. 7 it can be summarized that the Cb-clusters with diurnal variation tend to appear more frequently when the upper-level trough covers that area or is just approaching.

6.2 An example of the Cb-clusters around the upper-level trough in Area N1 in “Meiyu”

Figure 9 presents the sequence of geopotential height field at the 500 hPa level at 12 UTC from 11 to 14 July 1979 based on the “Daily Weather Maps” issued by the JMA. The large positive vorticity area \((V_{R50} > 3 \times 10^{-5} \text{ s}^{-1})\) and the center in question is also shown in Fig. 9. The surface maps at 00 and 12 UTC 13 July are indicated in Fig. 10. Figure 11 shows the GMS IR imageries at 00 and 12 UTC on 13 July 1979. The locations of the Cb-clusters identified by the criteria mentioned in 2.1 are also shown by lettering.

A trough at 12 UTC 11 July, corresponding to the vorticity center around 46°N/97°E, moved eastward to reach ~46°N/115°E at 12 UTC 13 July (the vorticity center is ~42.5°N/118°E, Fig. 10). The trough became a cut-off low with a closed contour of \(Z_{500} = 5640 \text{ gpm}\) at 12 UTC 13 July (Fig. 9). It should be also noted that the surface-level low (Fig. 10) is nearly in the same location as the 500 hPa-level low and that the 500 hPa-level low seems to be somewhat different from the developing baroclinic instability wave. This cut-off low slowly moved eastward and the closed contour of \(Z_{500} = 5640 \text{ gpm}\) disappeared at 12 UTC 14 (Fig. 9).

Five Cb-clusters (the clusters B to F) are seen around 40–50°N/105–125°E at 12 UTC 13 July (Fig. 11b). Besides, many deep convective clouds with horizontal scale smaller than 100 km in diameter also existed around there. These Cb-clusters and the smaller-scale convective clouds seem to be embedded in the large-scale cloud system associated with the upper-level low. The deep convect-
Live clouds (smaller than 100 km in diameter) exist there also at 00 UTC 13. However, the total area of these Cb-clusters at 00 UTC seems to be smaller than that at 12 UTC 13. Thus the deep convective clouds tend to be more activated at 12 UTC in Area N1 in “Meiyu” than at 00 UTC.

Ninomiya (1989) examined the cloud distribution in East Asia during early summer in 1979. He pointed out that deep convective clouds tend to appear frequently not only in the Baiu frontal zone but also around the “Baiu trough” just to the north of it (extending from ~60°N/170°E to ~35°N/115°E), during early June to early July. According to his study, the deep convective clouds around the Baiu trough appeared when slow-moving upper-level cut-off lows approached. The Cb-clusters in Area N1 in “Meiyu” as described in the present study would correspond to them. Furthermore, the present study shows that such convective clouds are subject to the strong diurnal variation with its maximum in the evening.

In general, the approach of the upper-level trough or low induces large-scale upward motion, and can give a triggering lifting of the air for the release of convective instability. The combination of this trigger with the surface heating seems to provide a favorable condition for the frequent appearance of the Cb-clusters with the strong diurnal variation in Area N1 in “Meiyu”. However, the Cb-clusters did not appeared so frequently in Area N1 in “Pre-Meiyu”, in spite of the frequent approach of the upper-level trough (Fig. 7) and the high ground surface tem-
perature as in "Meiyu" (Fig. 6). So, in addition to these two factors, another factor should be also considered. It is discussed in the next subsection.

6.3 Mean specific humidity increase in the lower layer and its role in the enhancement of instability

Figure 12 represents the meridional distribution of specific humidity at the 850 hPa level (Q850) averaged for 110 to 120°E for the three periods. It
Table 2. Mean values of specific humidity (Q850, in g kg⁻¹), potential temperature (θ850, in K) and relative humidity (RH850, in %) at the 850 hPa level, difference of potential temperature between the 500 hPa level and 850 hPa level, (θ500 - θ850, in K), that of equivalent potential temperature, (θ500 - θe850, in K) and horizontal divergence at the 850 hPa level (DV850, in 10⁻⁶ s⁻¹) in Area N1 for each period. “Daily” in this table indicates the mean for 00 and 12 UTC and “12Z-00Z” means the difference between them.

<table>
<thead>
<tr>
<th></th>
<th>Q850</th>
<th>θ850</th>
<th>RH850</th>
<th>θ500 - θ850</th>
<th>θ500 - θe850</th>
<th>DV850 12Z-00Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;Pre-Meiyu&quot;</td>
<td>5.9</td>
<td>301.7</td>
<td>48</td>
<td>+13.9</td>
<td>+1.2</td>
<td>+0.3</td>
</tr>
<tr>
<td>&quot;Meiyu&quot;</td>
<td>8.2</td>
<td>304.6</td>
<td>54</td>
<td>+15.4</td>
<td>-1.5</td>
<td>-1.7</td>
</tr>
<tr>
<td>&quot;Meiyu&quot; - &quot;Pre-Meiyu&quot;</td>
<td>+2.3</td>
<td>+2.9</td>
<td>+6</td>
<td>+1.5</td>
<td>-2.7</td>
<td>-2.0</td>
</tr>
</tbody>
</table>

is very interesting that Q850 increased considerably by 2-3 g kg⁻¹ from “Pre-Meiyu” to “Meiyu” even in Area N1, which is located to the north of the Baiu frontal zone in China in both periods. Table 2 indicates the averaged values of thermodynamical variables together with the horizontal divergence at the 850 hPa level (DV850) for Area N1 in “Pre-Meiyu” and “Meiyu”. As for DV850, the difference between 12 UTC and 00 UTC (12 UTC-00 UTC) is shown. The changes in these values from “Pre-Meiyu” to “Meiyu” are also presented (“Meiyu”-“Pre-Meiyu”). Although potential temperature at the 850 hPa level (θ850) in Area N1 increased slightly from “Pre-Meiyu” to “Meiyu”, the rise of Q850 is largely reflected by that of relative humidity. Note that the potential temperature difference between the 500 and 850 hPa levels (θ500 - θ850) in Area N1 is greater in “Meiyu” than in “Pre-Meiyu”, in spite of the rise of θ850 from “Pre-Meiyu” to “Meiyu”. It is due to the rise of low-level moisture content that contributes to the increase in instability for deep moist convection in Area N1 in “Meiyu”.

Murakami and Huang (1984) and Kato (1985b) pointed out, based on the case studies for 1979, that events with relatively large daily rainfall amount to the north of the Baiu frontal zone appeared much more frequently in “Meiyu” than in the previous stages. Murakami and Huang (1984) suggested that the increase in rainfall amount to the north of the Baiu frontal zone (North China) was accompanied
by the passage of meso-α-scale or synoptic-scale disturbances originating from the eastern foot of the Tibetan Plateau. The increase in the time-averaged specific humidity in Area N1 in “Meiyu” (further northern region) might be partly related to the situation mentioned in Murakami and Huang (1984) and Kato (1985b). However, how the moisture in Area N1 increases from “Pre-Meiyu to “Meiyu” is still a remaining problem.

Thus it is concluded that the combination of the three factors, i.e., (1) the frequent approach of a slow-moving upper-level low, (2) the rise of time-averaged specific humidity in the lower layer which resulted in the increase in convective instability, together with (3) the heating from the ground2, would provide a favorable condition for the frequent appearance of Cb-clusters with strong diurnal variation in Area N1 in “Meiyu”.

### 6.4 Further discussions on the role of the surface heating

Finally we would like to discuss the possible role of the heating from the ground. The time-averaged DV85 in Area N1 in “Meiyu” is larger at 12 UTC than that at 00 UTC (Table 2). This would be favorable for the activation of the Cb-clusters in the evening, by triggering large-scale upward motion for lifting an air parcel to the level of free convection (LFC).

Figure 13 presents the sea-level pressure (PSEA) field averaged for “Meiyu” based on twice-daily values of ANLMON. From the arid region to Area N1 (around 45°N/90–120°E), lower pressure region can be seen in the time-averaged field. Although the region with the maximum amplitude of diurnal variation of PSEA is located somewhat northeastward from Area N1, the lower pressure seems to be more enhanced at 12 UTC than that at 00 UTC (see also an example for 13 July in Fig. 10). Thus the seasonal enhancement of triggering large-scale upward motion in the evening might be associated with the deepening of the surface-level low in the seasonal mean field in the evening.

The surface heating in Area N1 might partly contribute to inducing large-scale upward motion, through the enhancement of a surface-level low (with horizontal extension more than 1000 km) at 12 UTC. In other words, the surface heating might contribute to the frequent appearance of the Cb-clusters in the evening in “Area N1” in “Meiyu”, through the diurnal variation of large-scale triggering upward motion. However, further studies are needed to examine the validity of that hypothesis.

### 7. Area C2 in “Mid-summer” (in the subtropical high area in Central China)

#### 7.1 An example of Cb-clusters

Recalling Fig. 7, the Cb-clusters in Area C2 in “Mid-summer” appear mostly in the subtropical high area identified by the 500 hPa level height field. Figure 14 presents the series of relative vorticity at the 500 hPa level (VR50) and horizontal divergence at the 850 hPa level (DV850) averaged for Area C2. The dates when Cb-clusters appeared at 12 UTC are marked by closed circles. In most cases, Cb-clusters developed in the evening. Although there are some fluctuations of VR50 and DV85 during “Mid-summer”, it is very interesting that Cb-clusters appeared even under the strong low-level large-scale divergence in the subtropical high area (e.g., during the period from 4 to 9 August), VR50 shows a large negative value and DV850 a large positive value).

Figure 15 shows a sequence of GMS IR imageries on 8 August 1979, as an example. Several meso-β or γ-scale convective clouds were generated rather randomly around 30°N/115°E at 06 UTC (14 BST). Some of the cloud areas expanded to merge with each other. At 12 UTC the cloud areas developed as isolated meso-α-scale Cb-clusters there. At 18 UTC (02 BST 09 August) they disappeared. Although pictures on other days are not shown here, a similar

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2 One might wonder if the heating from the ground could be actually strong even under the large-scale cloud systems mentioned in 6.2. As shown in Fig. 11, all the area of that system is not covered with the large-scale clouds. Iwasaki and Takeda (1993) also pointed out that the areal-mean total cloud amount in North China was not so large (only 10 to 40 %) when the Cb-clusters appeared. Thus the ground surface can receive considerable insolation even in such situations (so far as the areal-mean value is concerned).
diurnal cycle of the Cb-clusters can be seen around Central China in “Mid-summer”. In short, the Cb-clusters with remarkable diurnal variation in Area C2 are isolated without being embedded in the large-scale cloud systems.

7.2 Discussions

Table 3 presents the averaged values of specific humidity at the 850 hPa level (Q850), equivalent potential temperature difference between the 500 and 850 hPa levels (θ500 − θ850), and horizontal divergence at the 850 hPa level (DV850) for Area C2 in “Mid-summer”. The former two are the mean for 00 UTC and 12 UTC and the latter is the difference between them (12 UTC−00 UTC). The time-averaged values for the period from 4 to 9 August are also listed. It is interesting that the large-scale horizontal “divergence” in the lower layer is generally stronger at 12 UTC (in the evening) than at 00 UTC (in the the morning), including the period from 4 to 9 August. Thus the Cb-clusters seem to develop in the evening in Area C2 in “Mid-summer”, even under the stronger large-scale divergence in the lower layer (i.e., downward motion) than in the morning.

Figure 16 presents vertical profiles of θe and saturated equivalent potential temperature (θe) at the station 57494 (Wuhan, ~30.5°N/114°E) at 00 UTC 8 August 1979, as an example. Although Q850 in Area C2 is especially large (about 13.5 g kg⁻¹) and the atmosphere is strongly unstable for deep moist convection (θ500 − θ850 was lower than −5 K) (Table 3), the LFC is relatively high (around the 700 hPa level for the case in Fig. 16). Maybe this is partly due to the large-scale downward motion (although an inversion layer was not found in that case). Furthermore, the large-scale downward motion would suppress the release of convective instability, especially in the evening, by diluting the buoyancy of the rising air parcel with entrainment of drier air.

However, the daily maximum of the ground surface temperature in Area C2 averaged for “Mid-summer” exceeds 50°C (Section 5). That value is higher than that in North China and Northeast China in “Meiyu”. Thus such intense surface heating in the daytime might enable the air parcel to be lifted to the LFC to release the strong instability for deep moist convection there against the large-scale downward motion.

Now it should be noted that the surface heating in Area C2 would not result in the enhancement of large-scale low-level convergence in the evening. Thus the horizontal scale of the upward motion for lifting the air parcel to the LFC in the daytime would be smaller than a few hundred kms. The mountain-valley breeze circulation on such a scale could give the meso-scale upward motion as a trigger for initiating the Cb-clusters over the complicated orography. However, we have no observational facts on the diurnal variation of meso-scale circulation over the complicated orography, nor any results by numerical models. The roles of the surface heating should be examined quantitatively in the future.

8. Summary and conclusions

The appearance frequency of the Cb-clusters (with diameter of more than 100 km) over China and large-scale conditions associated with their diurnal variation were examined based on the observational data from June to August 1979. Analysis was made referring to the seasonal transitions of the Baiu (Meiyu) frontal zone over China, i.e., “Pre-
Meiyu” (1–17 June), “Meiyu” (20 June–22 July) and “Mid-summer” (23 July–17 August). The main results are as follows.

(1) The Cb-clusters appeared frequently, not only in the Baiu frontal zone, but also in the region from North China to Northeast China (38–50°N/110–125°E, Area N1) in “Meiyu”, and Central China (25–35°N/110–120°E, Area C2) in “Mid-summer”. While the Cb-clusters around the Baiu frontal zone in Central China in “Meiyu” appeared both in the daytime and night time, those in Area N1 in “Meiyu” and in Area C2 in “Mid-summer” presented strong diurnal variation with a maximum in the evening. The daily maximum of ground surface temperature ($T_g$ max) in these two cases was very high.

(2) In Area N1 (just between the Baiu frontal zone and the polar frontal zone) in “Meiyu”, the Cb-clusters with diurnal variation mainly appeared within the large-scale cloud systems associated with slow-moving upper-level lows or troughs. The specific humidity in the lower layer increased in “Meiyu”, compared to that in “Pre-Meiyu”. These two factors would provide a favorable condition for frequent appearance of Cb-clusters through the increase in convective instability as well as strong heating from the ground. The large-scale horizontal convergence in the lower layer was stronger at 12 UTC than at 00 UTC, which would contribute to the initiation of Cb-clusters developing in the evening.

(3) Although Area C2 was dominated by the subtropical high in “Mid-summer” and although the low-level divergence was generally stronger at 12 UTC than at 00 UTC, the Cb-clusters (without being embedded in large-scale cloud systems) developed very frequently in the evening. Strong surface heating in the daytime ($T_g$ max exceeds 50°C) could contribute to generating meso-scale upward motion as a trigger for the release of strong convective instability, even in the subtropical high area.

Table 3. Mean values of specific humidity at the 850 hPa level, Q850 (g kg$^{-1}$), equivalent potential temperature difference ($\theta_{e,850} - \theta_{e,850}$) (K) and horizontal divergence at the 850 hPa level, DV850, (10$^{-6}$ s$^{-1}$) in Area C2 in “Mid-summer”. "Daily" in this table indicates the mean for 00 and 12 UTC and "12Z-00Z" the difference between these times. The mean values for 4–9 August are also listed.

<table>
<thead>
<tr>
<th></th>
<th>Q850</th>
<th>$\theta_{e,850} - \theta_{e,850}$</th>
<th>DV850</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;Mid-summer&quot; Daily</td>
<td>13.5</td>
<td>-5.7</td>
<td>+1.5</td>
</tr>
<tr>
<td>4–9 August Daily</td>
<td>13.4</td>
<td>-8.7</td>
<td>+1.7</td>
</tr>
</tbody>
</table>

The present results not only show the different factors of large-scale atmospheric systems on the frequent appearance of the Cb-clusters with diurnal variation between the two regions, but also presents some interesting problems on the roles of the heating from the ground. The heating from the ground could induce diurnal variation of large-scale divergence in the lower layer as a trigger for initiating the Cb-clusters with diurnal variation in North China to Northeast China in “Meiyu” (together with the trigger by the upper-level trough). On the other hand, the heating from the ground could generate a meso-scale local circulation in a region with complicated orography and its updraft branch could give the trigger in Central China in “Mid-summer”. However, it is necessary to examine the detailed roles of the surface heating in the future.

Acknowledgements

The authors wish to express their thanks to the members of Laboratory of Atmospheric Water Cycle, Institute for Hydrospheric-Atmospheric
Sciences, Nagoya University, for their valuable discussions. They also appreciate the critical comments by the editor and the two anonymous reviewers for improvement of this manuscript. The present analysis was made mainly by using the Computation Center of Nagoya University.

References


中国東部における積乱雲群出現の日変化と総観場の解析 (1979年6~8月)

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中国東部の大陸上のCb群(直径100 km以上の積乱雲群)の出現状況、及びその日変化に関連した地表面温度や総観場の特徴について、1979年6~8月のデータに基づく解析を行った。大陸上の梅雨前線帯の位置や特徴の季節変化に準拠して、“Pre-Meiyu”(6月1～17日、梅雨前線帯の華中への北上)、“Meiyu”(6月20日～7月22日、華中の梅雨最盛期)、“Mid-summer”(7月23日～8月17日、華中の盛夏期)の3つの時期について調べた。主な結果は次の通りである。

(1)“Meiyu”期の華中では昼夜を問わずCb群が多数出現したが、“Meiyu”期に梅雨前線帯北方に位置する華北・中国東北区(Area N1)や盛夏期の華中(Area C2)でも、12 UTC(北京標準時で20時)頃ピークとなる顕著な日変化を伴って、Cb群が多数出現した。

(2)梅雨前線帯と寒帯前線帯にされる“Meiyu”期のArea N1では、動きの遅い上層トラフに対応する大規模システムの雲系に組み込まれた形で、日変化するCb群が出現しやすかった。この時期にはまだ梅雨前線帯の北側にある本地域でも、梅雨前線帯が華南から華中へと北上した6月20日頃を境に、下層の比湿が増加した。この比湿の増大は湿潤対流に対する安定度の悪化をもたらし、上層トラフ接近、日中の地面加熱と組合わせて、日変化するCb群の顕著な気象変化を伴ったものと考えられる。

(3)盛夏期 (“Mid-summer”)の華中(Area C2)では、華北帯高気圧に覆われ、かつマクロスケールでの領域平均の下層発散が夕方に強い傾向にも関わらず、Cb群出現頻度が夕方にピークをもつ日変化を示した。本地域で特に高い日中の地表面温度による加熱は、強い対流不安定を顕著化させるトリガーとしてのメソスケールでの上昇流を与える可能性があり、今後の検証が必要である。