AGEOSTROPHIC CIRCULATION ASSOCIATED WITH A STATIONARY BAIU FRONTAL CLOUD BAND

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1 Introduction

The Baiu front is a stationary front formed between the tropical airmass over the western Pacific Ocean and the polar airmass over the Asian Continent. The front extends from southern part of Japan to the China Continent in late spring and early summer. The Baiu front is one of the most important water source in Japan, while a precipitation system associated with the front occasionally causes torrential rain and flood in southern part of Japan.

During the Baiu season of 1997, a large amount of precipitation was brought by the Baiu frontal cloud band in the Kyushu District, Japan. An intense rainfall was lasted during the period from 5 to 12 July 1997. The accumulated rainfall amount was reached to more than 1000mm in the mountainous area and more than 600mm in the plain area of the Kyushu District during the week. As a result, some floods and land slides occurred. Satellite images showed that a cloud band extended from the China Continent to Japan along the Baiu front. The long-lasting rainfall was associated with the cloud band.

In this paper, we will describe vapor and ageostrophic circulation fields associated with the Baiu front. The purpose of this study is to clarify their characteristic structures to maintain the cloud band and the rainfall. [1]

2 Data

The Geostationary Meteorological Satellite (GMS) images, meteorological radar data, and the global objective analysis (GANAL) provided by the Japan Meteorological Agency were mainly used in this study. The horizontal resolution of GANAL is $1.25° \times 1.25°$ and every 6 hours.

3 Clouds and synoptic-scale field

The Baiu season in 1997 started in early June and ended in the middle of July. It was characterized by a heavy rainfall in the Kyushu District from 5 to 12 July 1997. During this period, the Baiu front was stationary around the region and cloud activity was intense. The averaged Tbb distribution during the period from 12 UTC, 6 July to 12 UTC, 11 July (Fig.1) shows a clearly defined low Tbb region extending from the China continent to Japan. The most intense area extended from the East China Sea to the Kyushu District of Japan. This cloud band was lasted for the period with a periodical intensification.

In the Kyushu District, a long-lasting rainfall was observed during this period associated with the cloud band. As a result, a large amount of precipitation was brought to the district and severe floods and land slides were occurred.

4 Moisture field

During the Baiu season including the heavy rainfall period, the Pacific Ocean high was dominant to the south of Japan. Along the west side of the high, a geostrophic flow was significant. A geostrophic jet was formed along the cloud band. Since the lower atmosphere was moist on the south side of the Baiu front, a vapor flux due to mainly geostrophic flow was large in the lower troposphere during the Baiu season (Fig.2).

While the large vapor flux was caused by the

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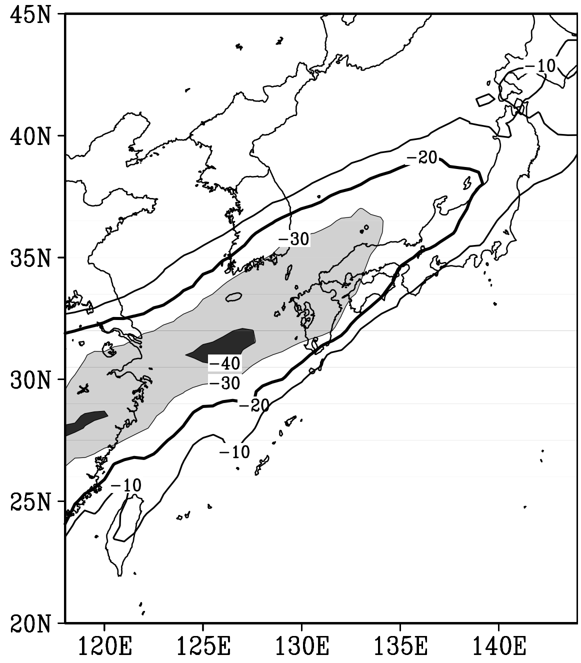

Figure 1: **Averaged Tbb (°C) distribution during the period from 12 UTC, 6 July to 12 UTC, 11 July 1997.**

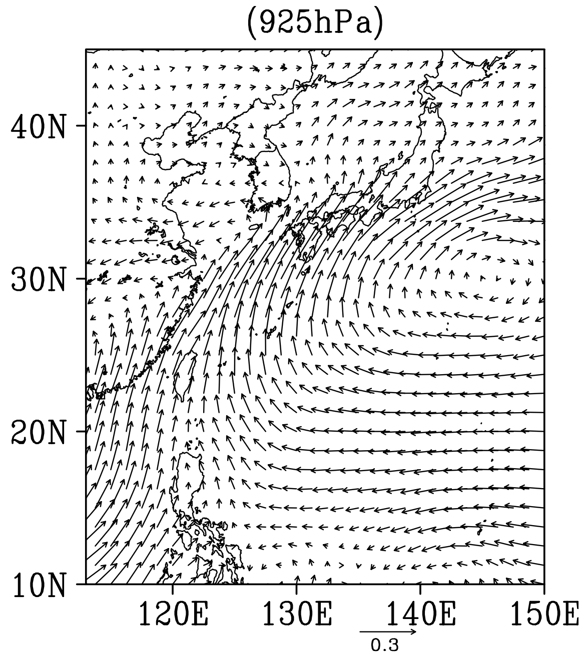

Figure 2: **Vapor flux at a level of 925 hPa averaged during the period from 12 UTC, 6 July to 12 UTC, 11 July 1997. The scale of flux is shown at the bottom of the figure and the unit is kg m $^{-2}$ s^{-1}.**

geostrophic flow, a divergence of vapor flux which is caused by ageostrophic flow is more important for cloud and precipitation. The vapor-flux divergence was calculated from the GANAL data for the period of the heavy rainfall. A significant negative divergence was found from the East China Sea to the Kyushu District in the lower atmosphere (Fig.3). This band of negative divergence corresponds to the Baiu frontal cloud band.

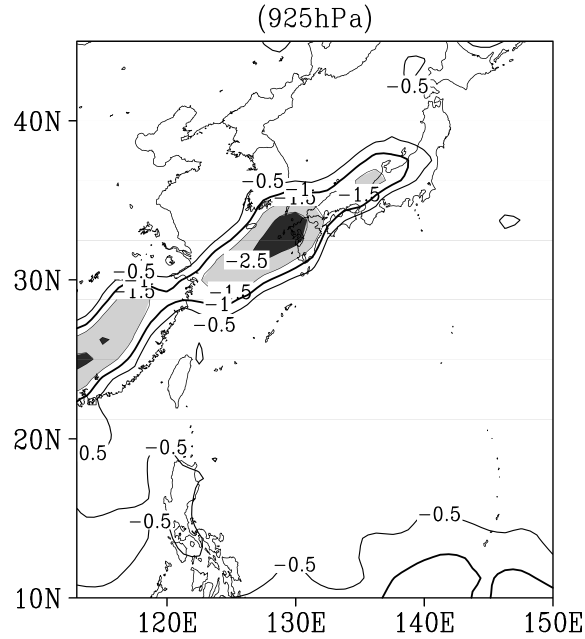

Figure 3: **Vapor-flux divergence at a level of 925 hPa averaged during the period from 12 UTC, 6 July to 12 UTC, 11 July 1997. The unit is 10^{-7} kg m $^{-3}$ s^{-1}.**

5 Ageostrophic circulation

The negative vapor-flux divergence corresponded to the long-lasting cloud band. This was mainly caused by the meridional component of the ageostrophic flow. We defined here the ageostrophic flow (u_a, v_a) as a difference between the velocity of wind (u, v) and the geostrophic velocity (u_g, v_g) as,

$$u_a = u - u_g, \quad (1)$$

$$v_a = v - v_g. \quad (2)$$

Figure 4 shows the vertical cross section of the ageostrophic meridional circulation. The Baiu front and the associated cloud band was located around 31°N. On the south side of the cloud band, a northward ageostrophic flow was significant below 700 hPa and a southward ageostrophic flow was significant at a level of 200–150 hPa. On the other hand, a southward ageostrophic flow was present on the north side of the cloud band below 700 hPa and a northward ageostrophic flow was present between 300 and 200 hPa. These ageostrophic flow caused a lower-level convergence and an upper-level divergence. Consequently, the upward motion was intense where the Baiu front and the cloud band were located.

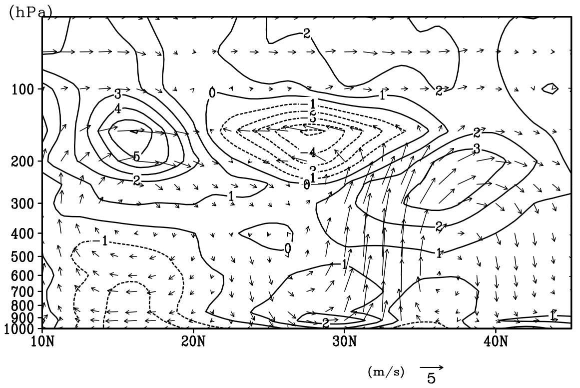

Figure 4: **Vertical cross section of the ageostrophic meridional circulation (v_a, w) averaged between 125 and 130°E and during the period from 12 UTC, 6 July to 12 UTC, 11 July 1997. Contour lines are v_a (m s^{-1}).**

The time-height cross sections of areal-averaged v_a (Fig.5) show that the lower-level northward v_a on the south side of the cloud band was present during both the rainfall period and other period. On the other hand, the upper level southward v_a on the south side of the cloud band was significant during when the cloud band was present. The lower-level southward v_a and the upper-level northward v_a on the north side of the cloud band was present during only the period of the heavy rainfall. This suggests that the lower-level convergence to form the cloud band was caused by the formation of the lower-level southward v_a.

In order to examine the dynamics of the meridional ageostrophic flow, we used the quasi-geostrophic momentum equation to calculate ageostrophic flow. In this manner, the ageostrophic velocity (u_a^g, v_a^g) is defined as,

$$u_a^g = -\frac{1}{f}\left(\frac{\partial v_g}{\partial t} + u_g\frac{\partial v_g}{\partial x} + v_g\frac{\partial v_g}{\partial y}\right), \quad (3)$$

$$v_a^g = \frac{1}{f}\left(\frac{\partial u_g}{\partial t} + u_g\frac{\partial u_g}{\partial x} + v_g\frac{\partial u_g}{\partial y}\right). \quad (4)$$

The time-latitude cross section of (u_a^g, v_a^g) also shows the southward ageostrophic flow on the north side of the cloud band during the period from 7 to 12 July 1997 (figure is not shown).

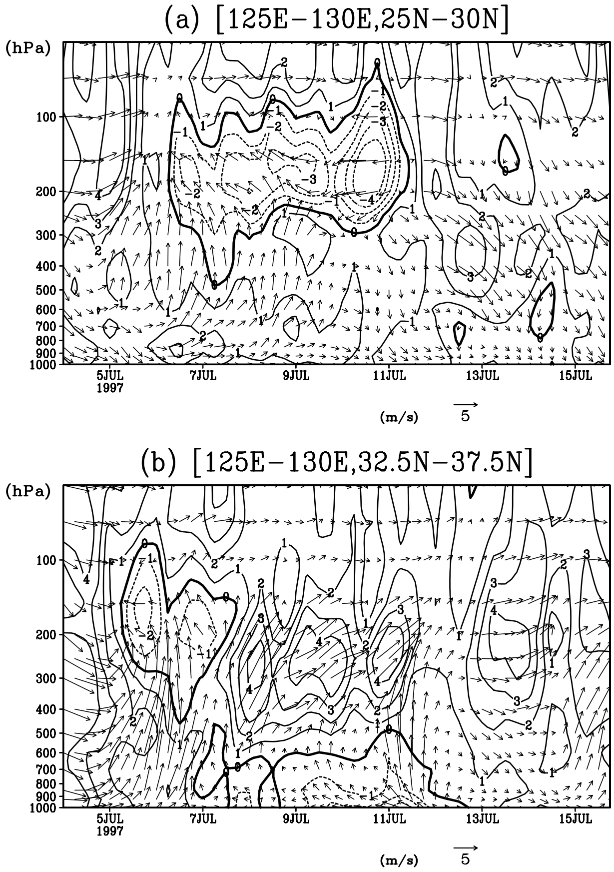

Figure 5: **Time-height cross sections of the ageostrophic meridional circulation (v_a, w) averaged in the areas of (a) the south side (125–130°E, 25–30°N) and (b) the north side (125–130°E, 32.5–37.5°N) of the Baiu front.**

These equations relate the ageostrophic circulation to the height field. The averaged height field between 125–130°E at a level of 925 hPa (Fig.6) shows that pattern of the height changed during the period which the cloud band was present. Before the cloud band was formed (Fig.6a), the height field of 925 hPa had a maximum around 25°N and decreased monotonically toward the north. During the period when the cloud band was formed (Fig.6b), the height field had a minimum around 34°N and a maximum around 36°N. This indicates that a weak high was located to the north of the cloud band. Equation (4) indicates that the weak high caused the lower-level southward v_a^g on the north side of the cloud band. After the cloud band dissipated (Fig.6c), the pattern of the height field returned to that before the cloud band was formed.

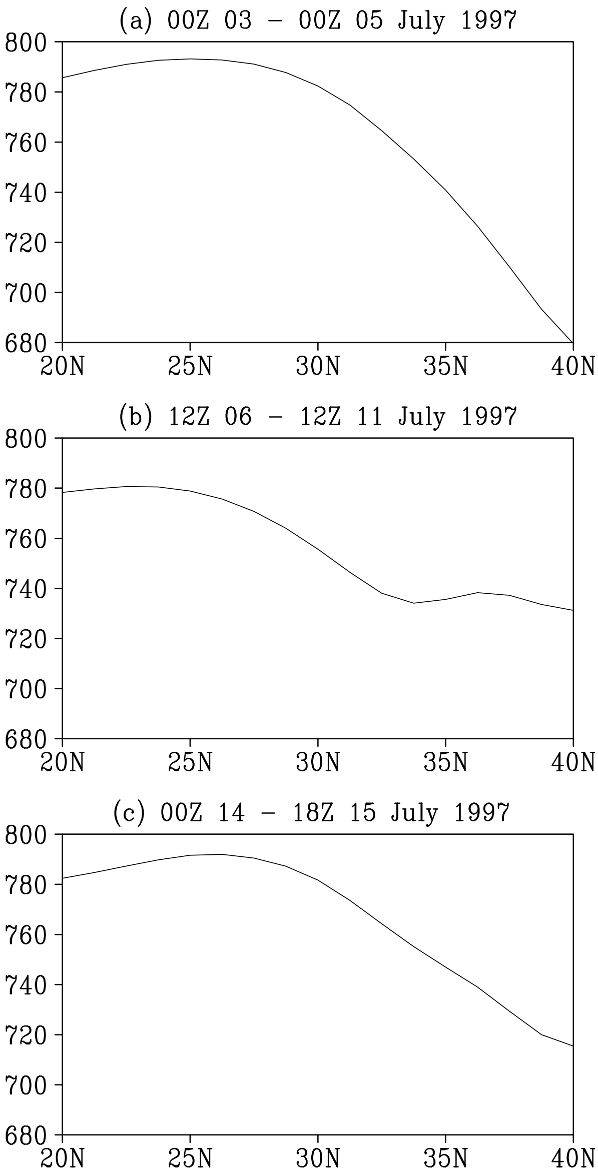

Figure 6: **Averaged height between 125–130°E at a level of 925 hPa averaged during periods of (a) 00 UTC, 3 to 00 UTC, 5, (b) 12 UTC, 6 to 12 UTC,11, and (c) 00 UTC, 14 to 18 UTC 15 July 1997.**

Since u_a^g and v_a^g are calculated from the quasi-geostrophic momentum equation (3) and(4), they are slightly different from u_a and v_a defined by (1) and (2), respectively. The discrepancy is related to a higher order deviation from the geostrophic wind. We should take account into the effect of diabatic heating due to condensation in cloud to explain the discrepancy.

6 Summary and conclusions

During the period 5 to 12 July 1997, the Baiu front extended from the China Continent to the western part of Japan through the East China Sea and stationary over the Kyushu District. A significant cloud band was maintained along the Baiu front for this period. This brought a large amount of precipitation in the district. In order to clarify the the structures of vapor and ageostrophic field associated with the Baiu front, we performed a data analysis using mainly the GANAL and GMS data.

On the south side of the cloud band, the lower troposphere was highly moist and a large moisture flux was present to the cloud band. The convergence of the moisture flux was large along the cloud band. The ageostrophic circulation was characterized by the lower-level northward v_a and the upper-level southward v_a on the south side of the cloud band and by the lower-level southward v_a and the upper-level northward v_a on the north side of the cloud band.

In order to examine the dynamics of the ageostrophic flow, we used the quasi-geostrophic momentum equations and found that the southward ageostrophic flow was caused by a mesoscale weak high on the north side of the cloud band. It was the mesoscale high that advected from the west and stagnated to the north of the Baiu front. We concluded that the vapor flux convergence and the resulted cloud band were caused by the stagnated mesoscale high and the associated southward ageostrophic flow.

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