NOTES AND CORRESPONDENCE

Structure of Line-Shaped Convective Systems Obliquely Training to the Baiu Front
Observed around the Southwest Islands of Japan

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Abstract

This study reveals a structure of line-shaped convective systems (LSCSs) observed around the Southwest Islands of Japan on June 10, 2006 using dual-Doppler analyses obtained from two X-band Doppler radars installed on Shimoji and Tarama Islands. Many LSCSs with lengths ranging from 20 km to 40 km form in a band-shaped precipitation system with a length exceeding 300 km along the Baiu front. The alignment directions of the Baiu front and the LSCSs are west-southwest to east-northeast and south-southwest to north-northeast, respectively. Thus, the alignment direction of the LSCSs is oblique to that of the Baiu front, and is parallel to the vertical wind shear vector between 0.5 km and 3 km in altitude.

These LSCSs consist of several precipitation cells. The precipitation cells generate only to the south of the southern edge of each LSCS, and move northward and decayed at the northern edge. The pre-existing cells in each LSCS hardly affect the successive generation of new cells. The generation area of precipitation cells coincides with low-level convergence along the Baiu front. The successive generation mechanism of new cells in the observed LSCSs and their structure shown in this study correspond to those in a humid environment, suggested in a previous numerical study.

1. Introduction

During the summer monsoon season (from May to July), the Baiu front extends in an east-west direction around the East China Sea and the Japan Islands. The southern region of the front is characterized by a warm, moist air mass and major south-westerly winds in the lower troposphere. On the other hand, the northern region is characterized by a cool and dry air mass. Thus, the Baiu front is the boundary between these two air masses. Mesoscale convective systems (MCSs) often develop around the Baiu front.

A typical MCS observed around the Baiu front has a line shape. Since the Baiu front corresponds to the convergence zone in the lower troposphere, in general, the alignment direction of a line-shaped precipitation system corresponds to that of the Baiu front (e.g., Ishihara et al. 1995; Takahashi et al. 1996; and Kato 2006). Lin et al. (1992) investigated a structure of a line-shaped precipitation system along the Meiyu front around Taiwan Island.
Uyeda et al. (2005) also reported a structure of a line-shaped precipitation system along the Baiu front around Okinawa Island. In both cases, convective cells moved along the Meiyu/Baiu front.

Schumacher and Johnson (2005) reported that one of the predominant MCSs that produced extreme rain events was the back-building (BB) type (Bluestein and Jain 1985), in which convective cells repeatedly formed upstream of the pre-existing ones. In general, the BB type was maintained by a low-level convergence between the environmental warm, moist air mass and cold outflow generated by evaporation cooling in the pre-existing precipitation cells (e.g., Fovell and Ogura 1988). However, Kato (1998) showed the maintenance process of the BB type in the moist environment around the Baiu front. Kato (1998) pointed out that the effect of evaporation cooling was quite small in the moist environment, and new convective cells formed repeatedly along the synoptic-scale convergence associated with the Baiu front. This structure was also presented by Kato and Goda (2001) and Watanabe (2007) and should be one of the typical MCSs around the Baiu front.

To study the structure of precipitation systems during the Baiu season around the Southwest Islands of Japan, an intensive observation using two Doppler radars belonging to Nagoya University was carried out on Shimoji and Tarama Islands in 2006. During this observation period, the Baiu front extended from west-southwest to east-northeast on June 10, as shown in the surface weather chart (Fig. 1a). At that time, a band-shaped precipitation system that consisted of many line-shaped convective systems (LSCSs) obliquely training to the Baiu front was observed by Japan Meteorological Agency (JMA) radar (Fig. 1b). The purpose of this study is to clarify the structure of the LSCSs obliquely training to the Baiu front using the observational data obtained by two X-band Doppler radars.

2. Data

Reflectivity and Doppler velocity data obtained by two X-band Doppler radars belonging to Nagoya University were used in this study. The two Doppler radars were installed on Shimoji and Tarama Islands (Fig. 1b). Observation range of these radars was 64 km in a beam direction. Sampling resolutions were 250 m and 1.2° in directions of the beam and azimuth, respectively. The Nyquist velocity of the Doppler radars was 16 m s⁻¹.

The Doppler radars obtained three-dimensional volume scanning reflectivity and radial velocity with 13 elevation angles (from 0.5° to 32.9°) every 6 min. For dual-Doppler analyses, both the reflectivity and radial velocity component were interpolated to a Cartesian grid volume using a weighting function (Cressman 1959). The grid spacings were 1.0 km and 0.25 km in horizontal and vertical directions, respectively. Doppler velocity unfolding was conducted manually so that the observed wind fields were continuous. Three-dimensional wind fields in precipitation regions were also calculated by the dual-Doppler analyses using the method developed by Gao et al. (1999). Precipitation cells
were defined as the areas surrounded by more than 34 dBZe within a closed curve at a height of 2 km. Upper-air sounding data obtained at Ishigakijima station were also used to describe the atmospheric environment around the Baiu front.

3. Results

As shown in Fig. 1b, the band-shaped precipitation system extending over 300 km was observed around the Southwest Islands of Japan by JMA radar. This band-shaped precipitation system was maintained about 6 hours from about 11 Japan Standard Time (JST: 9 hours ahead of UTC) to 17 JST. The propagation speed of the band-shaped precipitation system in the line-perpendicular direction detected from JMA radar data was quite slow, ranging from 2.6 m s\(^{-1}\) to 3.3 m s\(^{-1}\). The alignment direction of the band-shaped precipitation system is west-southwest to east-northeast and is same as that of the Baiu front. Each LSCS with a length ranging from 20 km to 40 km aligns from south-southwest to north-northeast. Thus, the LSCSs align oblique to the Baiu front.

To examine the structure of the LSCSs obliquely training to the Baiu front, three-dimensional reflectivity and wind field data obtained by dual-Doppler analyses around Shimoji and Tarama Islands were used. Some parts of the LSCSs were located in the range of the dual-Doppler analyses. Figure 2 shows the horizontal distribution of reflectivity and horizontal wind vectors at a height of 2 km at 1448 JST. High reflectivity areas consist of several precipitation cells. The horizontal scale of precipitation cells is about 5 km to 10 km. One alignment group of precipitation cells coincides with one of the LSCSs shown in Fig. 1b. Thus, the LSCSs consist of several precipitation cells.

Figure 3 shows a time series of the radar reflectivity, targeting the LSCS shown in Fig. 2, observed every 6 min from 1442 JST to 1506 JST. Each precipitation cell moves northeastward at a speed of about 30 m s\(^{-1}\), which corresponds to the horizontal wind velocity at a height of about 3 km. The LSCS could move east-northeastward at a speed of about 17 m s\(^{-1}\), if the center of the LSCS was defined by the midpoint between its northern and southern edges. In addition, precipitation cells are generated only to the south of the southern edge of the LSCS. Precipitation cells move relatively northward in the LSCS and decay at its northern edge.

Figure 4 shows the vertical section of reflectivity and wind vectors in the LSCS aligning in the X-Y line in Fig. 3 at 1448 JST. The precipitation cell located in the southern region (cell A) has a lower echo-top height (about 5.0 km) compared with the northern one and is occupied by updrafts. The maximum upward velocity in cell A is about 5 m s\(^{-1}\). Thus, cell A has characteristics of the developing stage in its life cycle. The cell located in the middle of the LSCS (cell B) has the highest echo-top height (about 6.2 km) and large maximum reflectivity (larger than 36 dBZe). The maximum upward velocity in cell B (about 1 m s\(^{-1}\)) is small compared with that in cell A. A high reflectivity region (larger than 32 dBZe) does not reach to the surface. Thus, cell B has characteristics of the latter developing stage. The cell located in the northern region (cell C) has downdrafts and a high reflectivity region reaching to the surface. The maximum downward velocity in cell C is about 2 m s\(^{-1}\); thus, cell C has characteristics of the mature or decaying stage. From Figs. 3, 4, it is recognized that new cells constructing the LSCS are generated on the upstream side of the pre-existing cells that propagate relatively northward.
Figure 5 shows the horizontal divergence at a height of 0.5 km that is calculated using wind distributions detected from the dual-Doppler data. The areas of large low-level convergence (divergence) appear in the southern (northern) region of the LSCS. The areas of large low-level convergence are found south of cell A and B, which means that cell A and B are in the developing stage. The area of large divergence is found at the lower level, associated with cell C that is in the mature or decaying stage. Wind direction and speed do not vary dramatically around the precipitation cells. Since the
downdrafts in the decaying cells are weak (Fig. 4),
the influence of the outflow from the pre-existing
cells should be quite small. It should be noted that
large convergence in the southern region of the
LSCSs corresponds to that along the Baiu front.

Figure 6 shows the time series of wind direction,
wind speed, temperature and precipitation amount
of 10 min observed at the Automated Meteorologi-
cal Data Acquisition System (AMeDAS) station
of Shimoji Island about 12 JST by JMA radar. Heavy (slight) rainfall from 1120 (1230) JST
to 1220 (1700) JST correspond to the passing of the
band-shaped precipitation system (adjoining strati-
form region) from northwest to southeast. Temper-
ature decreases only less than 2°C when the band-
shaped precipitation system passed over the station
at about 1150 JST. Simultaneously, wind direction
changed from south-southwesterly to westerly and
southwesterly.

Figure 7 shows vertical profiles of relative hu-
midity, equivalent potential temperature and satu-
rated equivalent potential temperature observed by
an upper-air sounding at Ishigakijima station at 21
JST. Although these profiles were obtained 6 hours
later than the radar observations, the location of the
Baiu front moved southeastward only about 50 km. The upper-air sounding site (Ishigakijima)
was located in the northern region of the Baiu front
both at about 15 JST (the time of radar observa-
tions) and 21 JST (the time of the upper-air sound-
ing observation). This indicates that these profiles
show the characteristics of the northern region of
the band-shaped precipitation system along the
Baiu front. Relative humidity below a 8-km height
is almost more than 90%; thus, the effect of evapo-
ration should be quite small. Further, a stable layer
is found between heights of 1.0 km and 2.3 km. Thus,
it is inappropriate to develop new convective cells in the northern region of the Baiu front.
Therefore, the new cells were developed only to the
south of the southern edge of the LSCSs where the
low-level convergence existed along the Baiu front.

4. Discussion

This study showed that the structure of the
LSCSs obliquely training to the Baiu front ob-
erved around the Southwest Islands of Japan on
June 10, 2006. The band-shaped precipitation sys-
tem organized by the LSCSs was quite similar to
the training line/adjoining stratiform (TL/AS) type
shown in Schumacher and Johnson (2005). Schu-
macher and Johnson (2005) showed that the con-
vective line consist of training convections moved
little in a line-perpendicular direction, since the
convective elements in their study moved in a line-
parallel direction. In this study, each LSCS moved
in a line-parallel direction, although the LSCS con-
sisted of several precipitation cells, not a single cell. Schumacher and Johnson (2005) also showed that the TL/AS type was typically formed in a moist, unstable atmospheric environment. The atmospheric environment in the southern region far from the Baiu front could be moist and unstable from JMA regional objective analysis data (not shown); therefore, the present case corresponds to the TL/AS type.

This study also showed that new cells in the LSCSs generated on the upstream side of the pre-existing cells that propagated relatively northward. This structure was quite similar to the BB type under the moist environment shown in Kato (1998) and Seko (2001). The different alignment between the LSCSs and the Baiu front was in common with that shown in Kato (1998). Kato (1998) concluded that the pre-existing cells did not affect on the generation of new cells, and this was attributed to the lack of evaporation cooling under the moist environment. Since the band-shaped precipitation system generated under the moist environment (Fig. 7), the effect of evaporation cooling could be also quite small in the present case. Downdrafts in the precipitation cells of the mature or decaying stages were weak (less than about 2 m s$^{-1}$; Fig. 4), and temperature decline around the surface was only 2 K when the band-shaped precipitation system passed over the observation area (Fig. 6). The low-level southward outflow from the northern cells was quite weak in this case (Figs. 4, 5); thus, the pre-existing cells in each LSCS could not affect the successive generation of new cells.

Figure 8 shows the hodograph averaged in the area indicated by the square in Fig. 2 around the LSCSs. The alignment direction of the LSCSs is not parallel to that of mid-level (at about 3 km) winds, and is parallel to the vertical wind shear between 0.5 km and 3 km in altitude. This relationship was also similar to that of transverse mode (T-mode) snow clouds observed over the Sea of Japan during the winter season (e.g., Yagi 1985).

Seko (2001) showed that the length of the line-shaped precipitation systems was attributed to the time-scale of the life-cycle and speed of precipitation cells in the BB type. In these LSCSs, the average life-time of each cell was about 22 min, and the relative speed projected onto the alignment of the LSCSs (south-southwest to north-northeast) of each cell was about 16 m s$^{-1}$. The length of the LSCSs was ranged to the product of the life-time and relative speed of each cell (about 21 km), because the precipitation cells generated only to the south of the southern edge of the LSCSs.

5. Summary

To study the structure of the precipitation systems during the Baiu season around the Southwest Islands of Japan, an intensive observation using two X-band Doppler radars belonging to Nagoya University was carried out on Shimoji and Tarama Islands in 2006. During this observation period, the band-shaped precipitation system along the Baiu front was observed on June 10, 2006. This band-shaped precipitation system was organized by the LSCSs obliquely training to the Baiu front and lasted for 6 hours. The structure of the band-shaped precipitation system was quite similar to the TL/AS type shown in Schumacher and Johnson (2005). The LSCSs with a length ranging from 20 km to 40 km consisted of several precipitation cells. The Baiu front and the LSCSs aligned from west-southwest to east-northeast and from south-southwest to north-northeast, respectively. Thus, the alignment direction of the LSCSs were oblique to that of the Baiu front and was parallel to the vertical wind shear vector between 0.5 km and 3 km in altitude.

The precipitation cells generated only to the south of the southern edge of each LSCS (the up-
stream side of the pre-existing cells), moved northward, and decayed at the northern edge, thus, the LSCS had characteristics of the BB type. The pre-existing cells in each LSCS could have a small influence on the successive generation of new cells. The location of the generation of precipitation cells could coincide with the low-level convergence along the Baiu front.

The successive generation mechanism of new cells in the observed LSCSs and their structure shown in this study corresponded to those in a humid environment, suggested in a previous numerical study shown in Kato (1998) and Seko (2001).

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