REMOTE SENSING AND HEAVY RAINFALL DISASTERS

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INTRODUCTION

In 1993, major disasters were caused by heavy rains in a great number of countries -- the United States, Nepal, Bangladesh, Japan, and others. It seems that abnormally heavy rains occurred all over the world in 1993 influenced by the El Niño event and other abnormal atmospheric situations. It is not an easy task to study the structure of an atmospheric disturbance, which generates heavy rain, by direct observations, because it is very severe and its spatial scale is smaller than the interval of routine upper–air sounding stations. Most heavy rains are formed mainly by the successive passing of cumulonimbus (Cb) clouds, although the large–scale atmospheric situations in which heavy rains are observed vary depending on the season and climatic region. It is still difficult at present to predict when and where heavy rain will occur, even if it is possible to predict the large–scale atmospheric situation which has the potential of heavy rain occurrence.

Remote sensors which measure the intensity of electromagnetic waves at various wave lengths are very useful instruments for studying and monitoring heavy rain, because atmospheric disturbances over a wide area can always be observed by remote sensors without setting them up in the disturbances themselves. Many kinds of active or passive remote sensors are now available, i.e., radar, doppler radar, and satellite–borne infrared or microwave radiometer. No remote sensor, however, is considered perfect. The efficient use of a remote sensor is highly dependent on the feature of a rain–making disturbance, especially its spatial and time scales. Here the usefulness of remote sensors for studying and monitoring heavy rain will be described mainly on the basis of the observation of heavy rain in Japan.

SPATIAL SCALE OF RAIN–MAKING CLOUD CLUSTER

It has been revealed by the observation of clouds by radars and satellite–borne remote sensors that heavy precipitating convective clouds (Cb–clouds), which have the spatial scale of meso–γ (2–20 km), often constitute the cloud clusters of meso–β scale (20–200 km) or meso–α scale (200–2,000 km) together with other types of clouds. The very interesting feature of a cloud cluster is that a meso–α scale cloud cluster is composed of several meso–β scale convective–cloud ensembles which consist of meso–γ scale convective clouds. In other words, the cloud cluster has multi–scale structure.

In Japan, heavy rainfall in the *Baiu* season is often generated in association with the cloud cluster of multi–scale structure, though all cloud clusters do not show multi–scale structure. Most of the heavy rainfall observed for the period of one to several hours are formed by a meso–γ scale Cb–cloud or a meso–β Cb–cloud ensemble; those for the period of about one day are due to a meso–α scale cloud cluster and those for several days are related to the successive passing of several meso–α scale cloud clusters. However, heavy rainfall observed on the windward side of mountains in the situation of an approaching typhoon (that is, so-called orographic heavy rainfall which shows a large amount of one–day rainfall) is caused by a formation mechanism which is rather different from rainfall due to a meso–α scale cloud cluster, though Cb–clouds are the most important rain–making components even in the case of a typhoon.

Figure 1 shows a meso–α scale cloud cluster which caused the heavy rainfall of 218 mm from 0.00 to 4.00 on 15 July 1985 in Sasebo City in the southwestern part of the Kyushu district. Rainfall for the amount larger than 100 mm was recorded in the very narrow region of 30 km x 60 km for these four hours. As seen in the figure, the cloud cluster of equivalent black–body temperature TBB (which corresponds roughly to the temperature of cloud–top) lower than –50° C was found at about 4.00 on 14 July over the continent and it arrived at the Kyushu district at about 22.00 as a meso–α scale cloud cluster after it travelled over the East China Sea. It stayed over the Kyushu district for several hours without moving eastward.

The areas of TBB lower than –70° C observed in the cloud cluster at 0.31, 2.05, and 2.31 on 15 July correspond to the group of developed Cb–clouds which produced heavy rainfall in Sasebo City. Its diameter is about 100 km (that is, meso–β scale). The life of a Cb–cloud ensemble is usually several hours and it can be observed as a group of intensive radar–echoes in its mature stage. At present it is very difficult to predict when and where a group of intensive radar–echoes will be formed. As shown in figure 1, however, a Cb–cloud ensemble which will produce heavy rainfall is often observed in a cloud cluster of very cold TBB, which can be detected by satellite–borne infrared remote sensors earlier than the formation of this Cb–cloud ensemble.

The meso–α cloud cluster of low TBB is one of the most remarkable phenomena in satellite imagery. It can be traced every hour by a geostationary satellite and, as seen in the cloud cluster at 2.05 in figure 1, its detailed TBB distribution can be given with spatial resolution of about 1 km by a NOAA–satellite infrared remote sensor. It would be a useful method for detecting the formation of heavy rainfall as early as possible to monitor the evolution of a meso–α scale cloud cluster by satellites, especially paying attention to the formation and behaviour of a meso–β scale area of very low TBB (the ensemble of developed Cb–clouds), and to detect the formation of a meso–β scale intensive radar–echo group in the cloud cluster.

In the *Baiu* season, many meso–α scale cloud clusters appear over the East China Sea, Yellow Sea, and Chinese continent. Some of them generate heavy rainfall in the Kyushu district and other regions of the islands of Japan after having travelled a long distance. Very heavy rainfall was observed at Nagasaki City in 1982, in which an hourly rainfall of 187 mm was recorded, which had also been generated by a meso–α scale Cb–cloud ensemble that remained in the Kyushu district after having travelled over the East China Sea.

BAND–SHAPED CUMULONIMBUS–CLOUD ENSEMBLE

It is very rare for a rainfall amount larger than 100 mm to precipitate at one site from a Cb–cloud, though the rainfall of 50 mm is possible because generally it travels with time. The phenomenon in which rainfall surpassing several hundred millimeters concentrates in a narrow region of several tens of kilometers in diameter within several hours (so–called "concentrated heavy rain") is formed in most cases by the successive passing of several heavy precipitating convective clouds over that region. In other words, it is produced by a meso–β scale Cb–cloud ensemble, particularly a band–shaped ensemble. If each constituent Cb–cloud moves in the direction of the band (in this case the band does not move as a whole in the direction orthogonal to it) and brings about intensive rain in nearly the same region in the band, the formation of concentrated heavy rain is certain.

The formation mechanism of a band–shaped Cb–cloud ensemble is not yet made clear, though there are many studies on its maintenance process. Therefore, it is still difficult to predict the formation of the band–shaped ensemble. At present it would be important in detecting concentrated heavy rain early to detect a band–shaped group of intensive radar–echoes and judge whether the group tends to be stationary as a whole or not.

Figure 2 indicates that intensive radar–echoes become grouped in a band with time over the sea near the Kyushu district. Convective radar–echoes of 10 km in diameter, which correspond to developed Cb–clouds, were formed successively. They were distributed irregularly before 7.00, but in a band–shaped group after 7.00. The height of their tops sometimes exceeded 15 km. As seen in figure 2, most of convective radar–echoes contain smaller intensive cellular echoes in them.

Interestingly, convective radar–echoes in the band were long–lasting as a result of the successive formation of smaller cellular echoes which had a life of about 30 minutes. The maintenance process of the band is shown schematically in figure 3. The long–lasting convective echo which moves in the direction of southwest to northeast is maintained due to the successive formation of new cellular echoes on its southeastern side (this type of long–lasting cumulonimbus–cloud is called "organized multicellular cumulonimbus cloud"), and the band–shaped radar–echo group is maintained due to the successive formation of new convective echoes at the southwestern edge of the band. It can be suggested that the band was formed in accordance with the appearance of long–lasting convective echoes and it was maintained by processes on two different spatial scales. This suggestion would be useful for the prompt detection of the formation of a band–shaped Cb–cloud ensemble by radar observation.

The band–shaped radar–echo group shown in figures 2 and 3 moved southward as a result of the travelling of constituent convective echoes in the direction which was deviated slightly southward from the direction of the band. If each convective echo moved in the direction of the band, concentrated heavy rain would have generated somewhere in the band. Since the movement of the organized multicellular Cb–cloud is determined by the combination of the movement of an individual cell and the formation place of new cells, it is not easy to predict whether the movement direction of constituent Cb–clouds coincides with the direction of the band–shaped group or not (that is, whether the band becomes stationary as a whole or not). It would be important to know at an early stage the stagnation tendency of a band–shaped intensive radar–echo group by radar observation.

MODIFICATION OF A CUMULONIMBUS CLOUD BY OROGRAPHIC EFFECT

The modification of a Cb–cloud by orographic effect is very important in the formation of heavy rainfall concentrated in a narrow region. In the islands of Japan, a large amount of rainfall is often observed in the windward region of mountains near the seashore, where heavy precipitating convective clouds are predominant. Recently short–range rainfall forecasting is made in many countries on the basis of the horizontal distribution of rainfall and the movement of rain areas which are observed quantitatively by radars and raingauges. The orographic effect on rainfall is an important problem too in this forecasting.

The orographic enhancement of rainfall would be partly due to the addition of rainfall from orographic clouds, which are formed by orographic upcurrent in the situation of strong low-level wind in mountain regions, to rainfall from Cb-clouds, and partly due to the dynamic development of Cb-clouds near mountains. But the orographic enhancement of rainfall seems to be more complicated.

Figure 4 shows that the radar-echo structure of a Cb-cloud changes as it approaches mountains from the seaside. Radar echoes are intensified twofold before and after the landing of the Cb-cloud -- i.e., the rainfall from the Cb-cloud is enhanced twofold as it approaches the mountains. This modification of a Cb-cloud by orographic effect is very often observed by radars.

The intensification of radar echoes in figure 4 does not necessarily mean an increase in the water amount of the Cb-cloud. It would have been caused mainly from the rapid development of many water droplets, which had not been detected by radar, into raindrops as a result of the change in the structure of airflow inside the Cb-cloud near the mountains. It is to be noted that the orographic enhancement of rainfall occurs in accordance with the rapid change in the three-dimensional structure of airflow and radar-echo in the Cb-cloud. It is not easy to observe this orographic enhancement in detail only with the usual long-range radar. Three-dimensional short-range radars, especially doppler radars, are useful for the detailed observation of orographic rainfall enhancement.

The distribution of airflow inside and outside the Cb-cloud can be given quantitatively by observing the doppler velocity of precipitation particles or other small electric-wave reflectors. The doppler radar is one of the most useful instruments for studying and monitoring heavy rainfall, because the change in the three-dimensional structure of airflow, which causes the changes in cloud structure and precipitation formation, can be observed by using it. But only precipitating clouds in limited range can be observed by the doppler radar and at least two doppler radars are necessary for observing airflow three-dimensionally. The network of doppler radars (NEXRAD) which is being constructed in North America will be an ideal network for monitoring the formation of heavy rainfall.

Figure 5 shows the distribution of airflow around a band-shaped Cb-cloud ensemble which approaches a mountain. In this case the change in the three-dimensional structure of airflow was observed quantitatively with spatial resolution less than 1 km every seven minutes by two doppler radars. The network of doppler radars is indispensable for studying the concentration of heavy rain in the narrow region due to the orographic modification of Cb-clouds, and for predicting or detecting the formation of concentrated heavy rain as early as possible.

In recent years the occurrence frequency of disasters caused by heavy rain concentrated in a very narrow region in a period shorter than one hour has increased in many cities of the world with the increase in the pavement area of cities. These kinds of disasters also occur in association with the rapid development or modification of a Cb-cloud. Doppler radars are useful for monitoring the rapid change in the structure of a Cb-cloud and preventing the progress of a disaster, even if the orographic modification of a Cb-cloud is not considered remarkable.

STRUCTURE OF A MESO-α SCALE CLOUD CLUSTER

The study on the structure and behaviour of a meso-α scale cloud cluster (MCC) will hold the key for the future success of monitoring or predicting the formation of heavy rain, although all meso–β scale heavy rain does not necessarily occur in sections of the MCC. As shown in figure 6, the MCC is often observed in the warm season in association with frontal activity around Japan. Figure 7 indicates the schematic representation of the structure of the MCCs shown in figure 6 which was made clear on the basis of the analysis of satellite data and radar data. This structure is typical of the MCC which moves slowly eastward. Several band–shaped Cb–cloud ensembles are distributed regularly in the direction of west to east, travelling eastward, and they are covered by extended clouds of low TBB. Rainfall is observed in the wide area beneath extended clouds.

An interesting fact in figure 6 is that the MCC is maintained for a long time by the successive formation of the new band–shaped Cb–cloud ensemble on its western side and the successive disappearance of the most eastern Cb–cloud ensemble. Therefore, the eastward movement of the MCC is much slower than that of the individual Cb–cloud ensemble. Its stationary state can result from the favourable combination of the velocity of the eastward moving Cb–cloud ensemble and the place of formation of the new ensemble relative to the most western one. The MCC B in figure 6 remained stationary for a while in spite of the fact that it remained over the sea.

It seems that most MCCs observed around Japan show the structure and maintenance process represented in figure 7. But in the case of a tropical MCC, a new Cb–cloud ensemble is often formed in front of travelling ensembles, not in the rear, although the structure of the MCC is similar to that shown in figure 7. Since intensive rain is observed many times somewhere inside the MCC, its behaviour and movement which can always be monitored by satellite–borne remote sensors would be very useful information for detecting or predicting the formation of heavy rain. Some persistent heavy rains observed over the period of a few days are caused by the successive passing of MCCs.

INFLUENCE OF GLOBAL–SCALE ATMOSPHERIC CHANGE ON HEAVY RAIN

In 1993, abnormally heavy rains and violent floods occurred in many places of the world, e.g., the Amazon River Basin, Yantze River Basin and Mississippi River Basin. Monthly rainfall amount recorded in July 1993 in Kagoshima is the largest since routine meteorological observation was started at the Kagoshima Meteorological Observatory in 1883, and the second largest daily rainfall amount was recorded this past August at the Observatory. It has been pointed out by many meteorologists that these abnormally heavy rainfalls might have been caused by the El Niño event and large–scale meandering westerly winds.

Recently it has been widely established, especially on the basis of satellite observations, that abnormal changes which were found in the formation frequency and amount of heavy rain in various regions of the world were closely associated with global–scale atmospheric changes. Some abnormally heavy rains in Japan –– Isahaya heavy rain, Nagasaki heavy rain, and 47.7 heavy rain –– occurred in the year of an El Niño event.

Major current topics in atmospheric sciences are the large intraseasonal variation of various atmospheric phenomena with a period of several to ten days. This variation is especially found in the tropics. Cloud amount also shows intraseasonal variation in various regions, rather independently of climatic difference. The appearance frequency of meso–α scale cloud clusters changes sometimes with a period of about thirty days around the islands of Japan. In addition to variation with a period of about thirty days, the large intraseasonal variation of rainfall amount with a period of about fifteen days is found in the early stage of *Baiu* over a wide region around the Kyushu district. This is related to the fact that water vapour amount, which is transported northward high in the western part of the Pacific, changes within a period of about fifteen days due to the variation in the east to west difference of pressure.

The large-scale time change in rain-making cloud-cluster activity, which occurs in various regions in association with global-scale atmospheric change, can be clearly detected by satellite remote sensing, although the relationship between both changes has not yet been clarified sufficiently. Some abnormally heavy rains in 1993 were observed as the abnormal formation and movement of cloud clusters. A large amount of rainfall in Kagoshima City in the period of July to August was also produced by the successive passing of many MCCs. It should be noted, however, that no MCC was observed around Kagoshima City in the case of the heaviest rain in this period which occurred from 4.00 to 8.00 on 6 August. This case implies that all heavy rains, especially concentrated heavy rains, cannot be detected only by the use of satellite-borne remote sensors.

CONCLUDING REMARKS

The monitoring of cloud clusters by satellite-borne remote sensors is very useful for detecting the possibility of heavy-rain formation as early as possible, including its relation to global-scale atmospheric change. Satellite remote sensing of clouds is now carried out on the wavelength of visible, infrared, or microwave range. A satellite (TRMM) loaded for the first time with a precipitation radar will be launched in 1997. Satellite-borne microwave radiometers and radars will be very useful for quantitatively observing the feature of rain-making cloud clusters, though their spatial or time resolution is rather coarse, if they are used together with visible and infrared passive remote sensors. It is expected that studies will be made, in particular, on the place of formation and process of a meso-β scale cumulonimbus-cloud ensemble, which has the large potential of heavy rainfall, in a meso-α scale cloud cluster.

Such a combination of a radar network and raingauge network as the Japanese radar-AMEDAS composite system is useful for the quantitative monitoring of rainfall over a wide area. If doppler radars are also used in short-range rainfall forecasting together with a radar-raingauge network, there is a possibility that the enhancement and concentration of rainfall by orographic effect can be predicted more quantitatively. In order to realize this quantitative prediction of rainfall, it is urgent to know how the grouping of developed Cb-clouds in a band and the orographic modification of Cb-clouds appear as the time evolution of their imagery are given by remote sensors.

The use of remote-sensing data in the numerical prediction of heavy rainfall is also expected as indirect efficient utilization. The quantitative prediction of an atmospheric disturbance which causes the formation of a meso-α scale cloud cluster, will be made possible by the numerical model of finer mesh size, though the computing method related to the evolution of Cb-clouds should be improved in quality if mesh size finer than 20 km is used in the model. In this case the important problem is how to make the initial condition of high resolution which is suitable for the numerical model of fine mesh size. It is not possible to make the initial data of high resolution from the data of routine upper-air sounding stations. It is especially difficult to get suitable initial data for the numerical model over the ocean. But observation by satellite-borne remote sensors can homogeneously make data of high resolution over a wide region. Data processing by four-dimensional analysis is sometimes necessary. It is desirable to improve the method of converting remote-sensing data concerned with clouds and precipitation into initial data which are suitable for a numerical prediction model

The use of remote sensors can lead to various possibilities for the reduction of heavy-rain disasters. It will be necessary to develop a method of utilizing remote sensors dependent upon the climatic region as well as the spatial and time scales of a rain–making disturbance, because such a disturbance has characteristics peculiar to the given climatic region. It is also necessary in order to realize the effective reduction of heavy–rain disasters in each region to study the climatology of heavy rain by remote sensing.

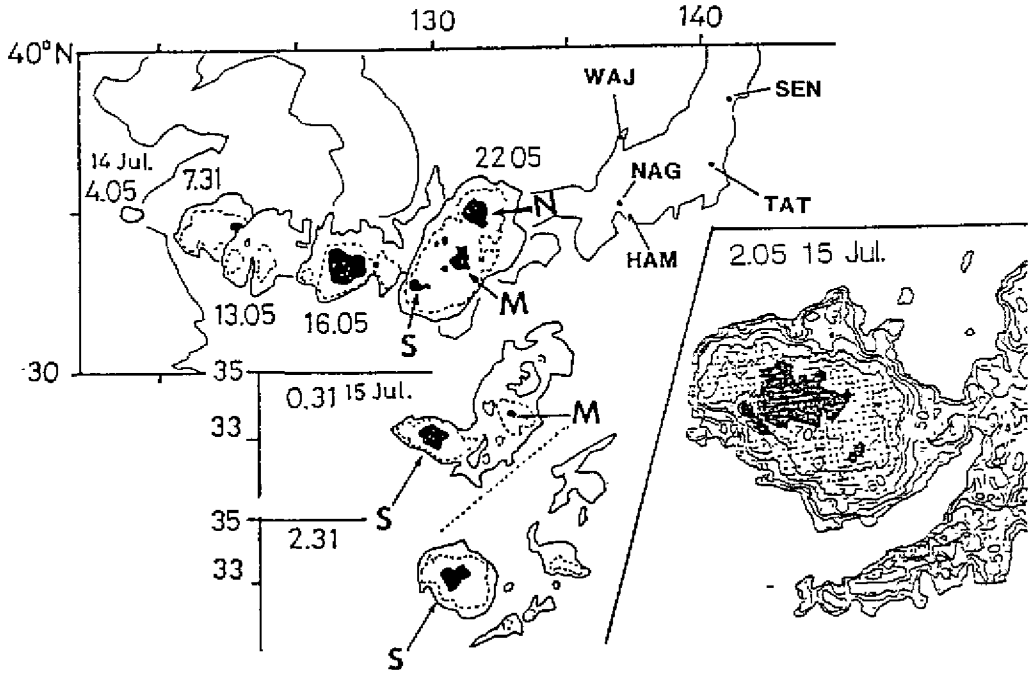

Figure 1. Evolution of a Meso-α Scale Cloud Cluster which Generated Heavy Rainfall in Sasebo City in the Kyushu District
Contours on left side of figure indicate TBB of −50° C, −60° C, and −70° C.

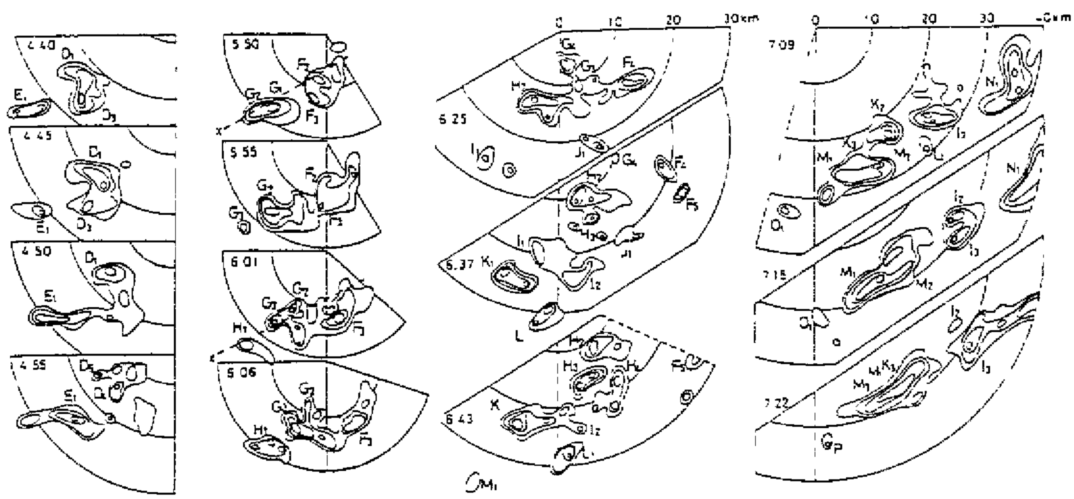

Figure 2. Time Variation of Radar-echo Distribution at 5 Km Level
Outermost contours show the intensity of 20dBZ and other contours are drawn every 5dBZ.

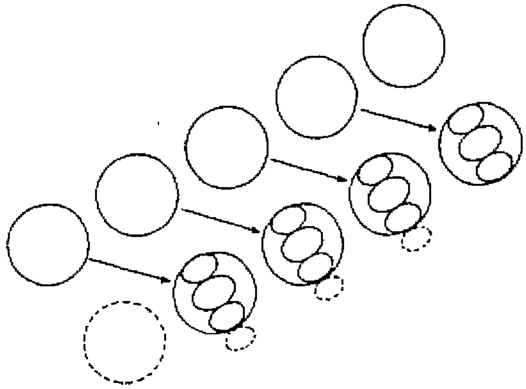

Figure 3. Schematic Representation of Maintenance of a Band–shaped Cumulonimbus–Cloud Ensemble
Small ellipse indicates a cell which comprises a cumulonimbus cloud.

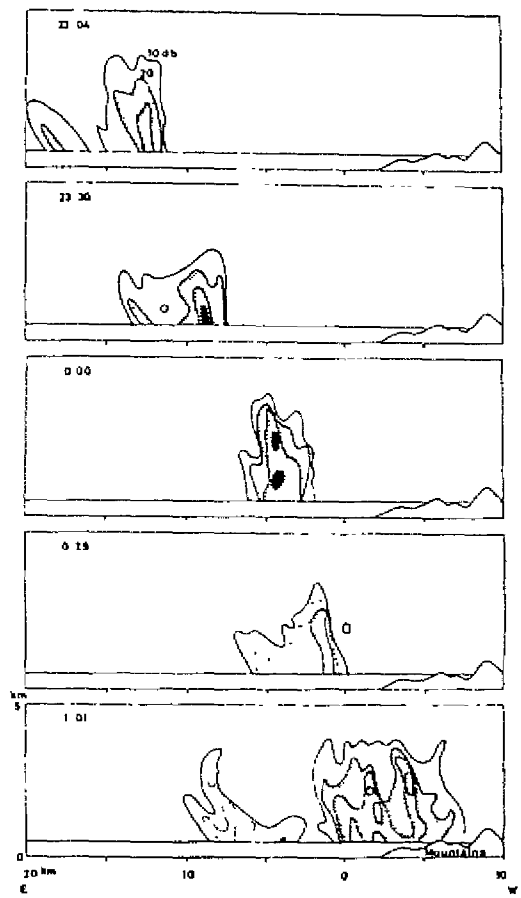

Figure 4. Change in Radar–echo Structure of a Cumulonimbus Cloud Approaching Mountain

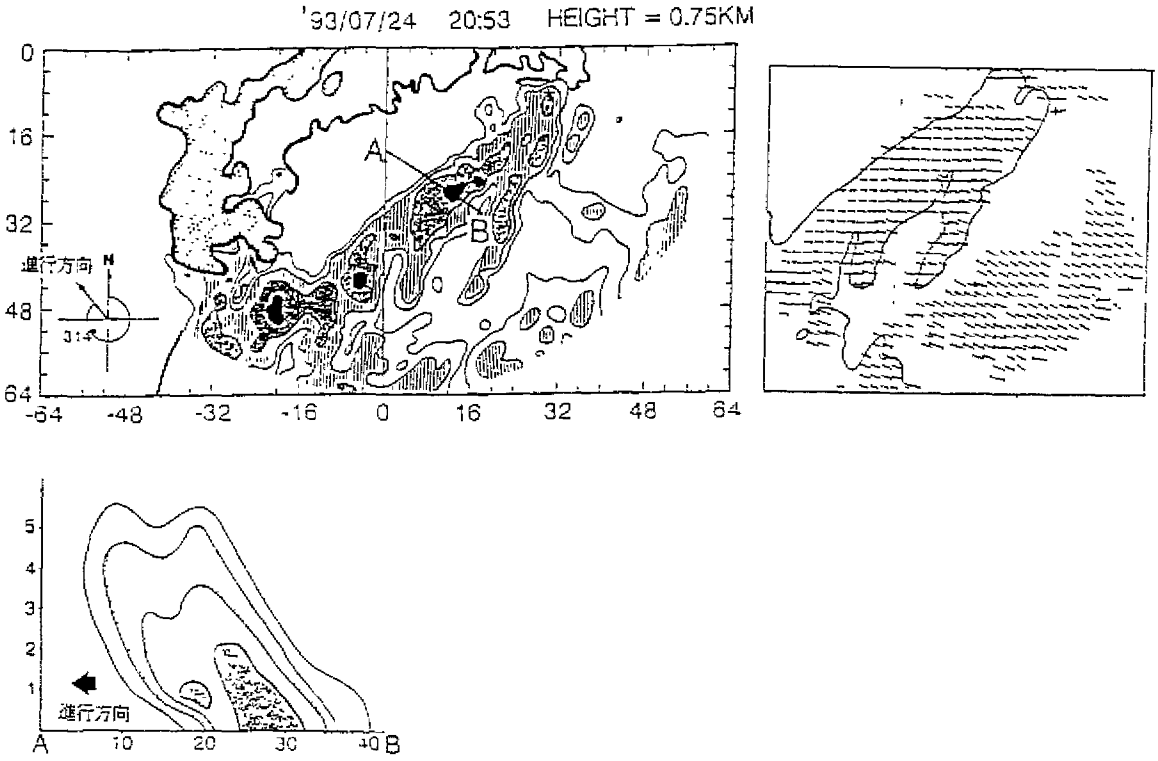

Figure 5. Landing Band-shaped Cumulonimbus-cloud Ensemble Observed by Two Doppler Radars
Outermost contour shows echo intensity of 10dBZ and other contours are drawn every 6dBZ.

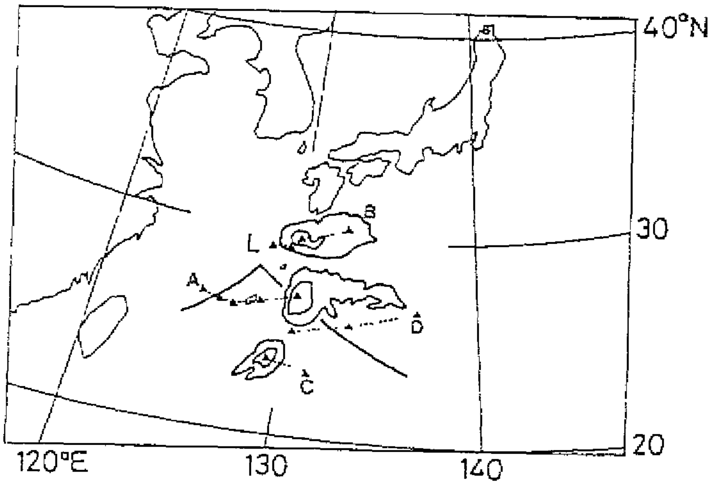

Figure 6. Meso-α Scale Cloud Clusters Observed around Islands of Japan
Contours show TBB of −40° C (outer) and −60° C (inner).

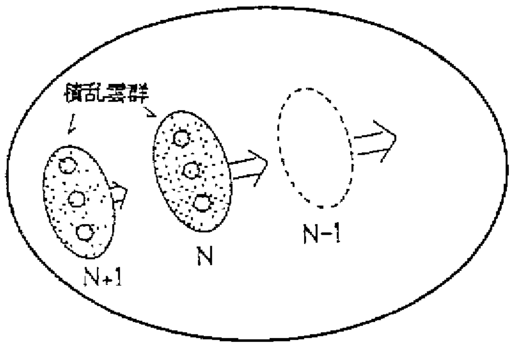

Figure 7. Schematic Representation of Structure of a Meso-α Scale Cloud Cluster