INHOMOGENEOUS FEATURES IN MEI-YU FRONTAL CLOUD SYSTEM*

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ABSTRACT

The structure of radar echo in stratiform cloud which was found in mei-yu frontal cloud system is generally inhomogeneous, especially in the structure of bright band echoes. The inhomogeneous structure of warm region in stratiform cloud and the shower feature of precipitation are closely related to the inhomogeneous structure of bright band and convective cells embedded in stratiform cloud.

During Summer time the mei-yu cloud system is an important precipitating system in the southern part of China. To study its structure is of great significance for weather forecast and understanding the physical processes of cloud and precipitation. Therefore, we have observed mei-yu frontal cloud system by use of 711 type radar (3 cm) and airplane at Tunxi, Anhui Province since 1979. It was found that the structure of stratiform cloud, especially the structure of its warm region appears to be inhomogeneous[1),2)]. This is a significant feature of cloud structure in mei-yu frontal cloud system. In this paper, we shall further analyse this inhomogeneous structure of stratiform cloud and study its effect on the precipitation.

I. INHOMOGENEOUS STRUCTURE OF THE STRATIFORM CLOUD

The inhomogeneous structure is one of features of radar echo structure in mei-yü frontal cloud system. In this cloud system, there are complicated cloud types, such as various stratiform clouds, convective clouds, and coexistance of stratiform cloud and cumulonimbus with heavy rainfall. "Stratiform cloud" to be discussed in this papar refers to that at least visual observation at the meteorological station can identify its stratified structure rather than other cloud type. The inhomogeneous structure of stratiform cloud is shown generally as follows:

1. *Convective Clouds Embedded in the Stratiform Cloud*

On PPI section, in a large region of echo there are many stronger irregular spots and patches with horizontal size from 2.0 to 4.0 km. They are echoes from convective cells embedded in stratifrom cloud. Their tops are generally in the vicinity of the 0°C isotherm. The reflectivity of convective cells is from 6.0 to 38.0 dbz. Usually, these cells do not produce thunder and lightning. Because convective cells hide in the stratiform cloud, it is difficult to find them from either satellite picture or visual observation on the ground. In case of many cells, they may directly cause a horizontally inhomogeneous structure in warm region of the stratiform cloud. For example, Fig.1 displays a convective cell below radar bright band whose top height is about 5 km, the horizontal size about 3.5 km and reflectivity factors above 37.0 dbz. The echo of

* Mei-yu —same as in P71.

1) Huang Meiyuan, Hong Yanchao and Wu Yuxia, Several features of radar echo in mei-yu frontal cloud system. Conf. on cumulus precipitation in the south of China, Changsha City, December 1981.

2) He Zhenzhen, Huang Meiyuan and Shen Zhilai, Some features of convective zone in warm stratiform cloud. Conf. on cumulus precipitation in the south of China, Changsha City, December 1981.

convective cell is much stronger than that of surrounding stratiform cloud. The observations made in northern China also show the existance of convective cells in the stratiform cloud system. This phenomenon is probably representative for the frontal cloud system.

Fig. 1. A convective cell embedded in stratiform cloud.

2. *The Downward Extending Echoes (DEE) in the Warm Region of Stratiform Cloud*

Sometimes, we can see that echo structure of stratiform cloud without convective cell (it is named pure stratiform cloud) is still inhomogeneous on PPI section. In a widespread region of relatively uniform reflectivity, there are some dot-like and mass-like higher reflectivity echoes as those of convective cells embedded in stratiform cloud. We see only some strong echo regions in weak stratiform cloud on PPI section. They are downward extension of precipitation or virga from the cores with strong reflectivity in the bright band (CSR) (their reflectivity is at least 5.0 dbz more than the surrounding echo) in stratiform cloud rather than convective cells on the RHI section through these strong echo regions. We call them as DEE. DEE, as well as the convective cells, may cause inhomogeneous structure in the warm region. Fig. 2 and Fig. 3 display two cases observed at Tunxi in 1980. In Fig. 2, the stratiform cloud echo contains some strong echo zones with irregular shape which are precipitation echo extending downward from CSR. In Fig. 3, there are only some strong echo regions in the stratiform cloud on PPI scan. Clearly, it is horizontal section of DEE originating from CSR at the height of about 5 km($\sim$0°C isotherm altitude from the radiosonde).

Description mentioned above shows that inhomogeneous structure in stratiform cloud may be caused either by convective cells which cannot easily be found on the ground, or by DEE in the warm region. But according to the radar observation, the DEE can be observed frequently, even for the stratiform cloud containing convective cells, the DEE also exists in it. To the authors' best knowledge, there are no published papers on the similar structure in other frontal cloud system yet. It is probably an important feature of structure in stratiform cloud in mei-yü frontal cloud system. The strong ascending air, high liquid water content and high temperature in warm region of stratiform cloud observed by the airplane[3)] are likely associated with the DEE. In addition, same structure is sometimes observed in upper stratiform clouds. For example, a clear horizontal echo band at a 6—8 km height can be seen on the RHI section in Fig.4. For Cs-As there are two echo regions with a stronger reflectivity more than 14 dbz and they are inhomogeneous in structure and reflectivity.

3) Echoes used in this paper are laminated in 5 db intervals unless otherwise stated.

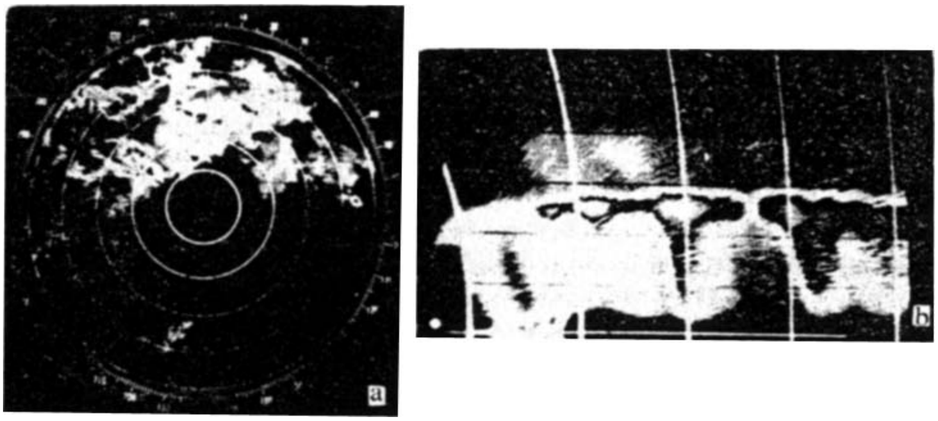

Fig. 2. Cores of high reflectivity in the bright band and corresponding DEE* (on 5 July 1980).
(a) PPI, 09:30, 5° elevation;
(b) RHI, 09:28, 340° azimuth.

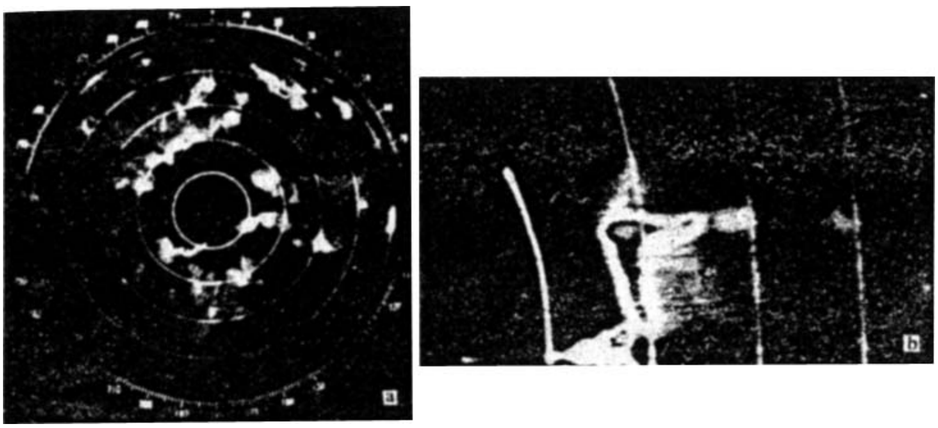

Fig. 3. Inhomogeneous structure in weaker stratiform cloud on 9 July 1980.
(a) PPI, 18:25, 5° elevation;
(b) RHI, 18:27, 340° azimuth.

Fig. 4. Inhomogeneous structure in upper stratiform cloud (14 July 1980).
Time: 06:20; Azimuth: 42°.

II. THE DEE IN THE STRATIFORM CLOUD

The DEE and convective cells are responsible for inhomogeneous stracture in the stratiform cloud, but the former may be of a specific structure feature in mei-yu frontal clour system, so that the analysis relating to problems on features and formation of DEE will be emphasized here.

1. *The Major Characteristics of the DEE*

The features of DEE from CSR are closely associated with those of the bright band. As it has been pointed out that the structure of radar bright band in mei-yu frontal cloud system is usually inhomogeneous. There are several cores with stronger reflectivity, which uncontinually distribute in the bright band on RHI section (Fig.2(b) and Fig.5). The maximum intensity, the horizontal size of the cores and the distance between the cores in the bright band directly affect corresponding parameters of DEE. The shape of virtical section of CSR is mostly oblate ellipsoid. The reflectivity factors of CSR vary from 6.0 dbz to 30.0 dbz, but usually are 19.0 dbz—24.0 dbz. On the other hand, the thickness of CSR and the distance between them are different as shown in Fig. 2(b) and 5. Generally, the CSR with high reflectivity corresponds to the strong DEE, but the reflectivity of the DEE is about 5 dbz lower than the CSR,. Intensity of the DEE reduces downward with height below the 0°C level (5 km). For instance, there are two CSR in Fig. 5(a), the stronger one locates at 43 km from the radar set and its DEE is also stronger and extends nearly to the ground. In addition, the reflectivity of DEE from this CSR is larger than 19.0 dbz at 4 km but only 14.0 dbz at 2 km. It shows that the intensity of the DEE reduces with decreasing height. As consistent with this fact, horizontal size of reflectivity contours of the DEE reduces downward as well, thus the DEE is shaped like a "funnel". The horizontal size of the DEE and the distance between them depend also on the same parameters of CSR. Statistical results for 102 CSR show that horizontal size of CSR ranges from 1.0 to 16.0 km with 5.4

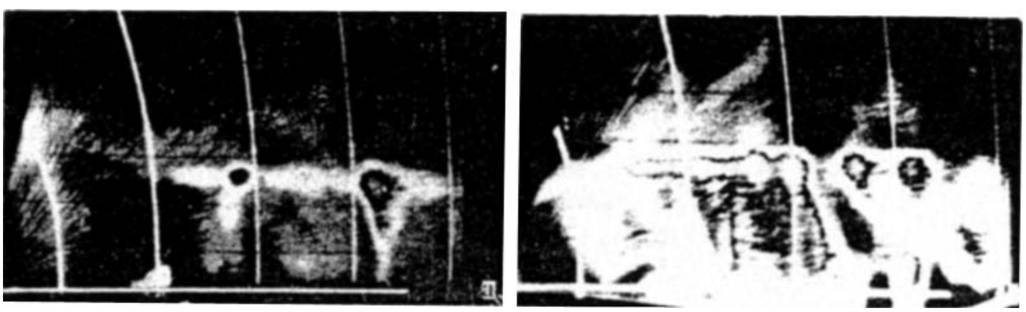

Fig. 5. Inhomogeneous bright band in stratiform cloud.
(a) Time: 14:36, 18 June 1980; Azimuth: 015°;
(b) Time: 11:51, 5 July 1980; Azimuth: 014°.

km as its average, 78% of them are between 1.0 to 5.0 km. Horizontal size of DEE is in a range of 1.0 — 5.0 km and its average value is 2.7 km. Distances between two CSR and two DEE vary in a wide range. The virtical thickness of CSR rangs from 200 m to 1500 m, 87% and 36% of them are 400 — 1000 m and 800 — 1000 m, respectively, the average value is 850 m. It indicates that the bright band of radar echo in mei-yu frontal cloud system is comparatively thick.

2. The Formation Process of DEE

According to the radar observation, in fact, the DEE results from the CSR. At first, echo spots are formed near below 0°C level, then the intensity of the spot increases gradually with the size, and eventually forms cores of high reflectivity near 0°C level, or the CSR. In the great majority of cases, the cores with a reflectivity larger than 14.0 dbz begin to extend downward and form the DEE. When there are many echo spots and the cores of high reflectivity have formed below 0°C level, the inhomogeneous bright band is composed of the cores. An example of DEE formation obtained from combination of the RHI and PPI scanned by tracking an echo spot is shown in Fig.6, The echo spot was located near 5.3 km MSL (the height of 0°C isotherm from radiosonde at 07:00 on 6 July 1980). At 14:35, the intensity of core with high reflectivity is larger than 24 dbz and DEE have been formed. After that, the end of DEE was falling down at a speed of 4 m/s (about the terminal velocity of raindrop with a diameter of 1.0 mm) from 14:35 to 14:40.

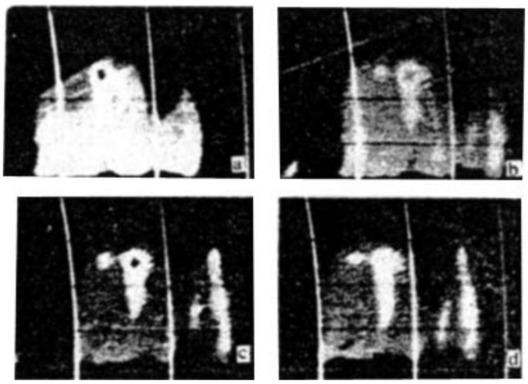

Fig. 6. The formation process of a DEE (6 July 1980).
(a) Time: 14:35, Azimuth: 50°; (b) Time: 14:37, Azimuth: 51°;
(c) Time: 14:38, Azimuth: 55°; (d) Time: 14:40, Azimuth: 55°.

The physical process of the CSR formation is worthy of further study. In view of the position of reflectivity core which is near 0°C level, it can be affirmed that its formation is related to the melting of ice crystal and snowflake falling from upper level. Primary theoretical calculation has shown that nonuniform structure of echo over bright band may be direct results in CSR of the bright band. If in the upper part of bright band there are some generating cells which have large size ice crystals of high concentration and the intensity of the bright band under these cells is high, then it will cause a horizontally inhomogeneous structure of bright band. From observations and analyses by Hobbs et al [1,2],there are certainly generating cells over upper frontal zone in cold frontal and warm frontal cloud system in company with extra-tropical cyclones. Ice crystals yielded and provided by generating cells play the role of the natural seeding in the stratiform cloud rainfall. In mei-yu frontal cloud system, a wide range of precipitation from stratiform cloud occurs usually in the northern side of the stationary frontal zone. Whether there are also generating cells producing larger ice crystals over the upper frontal zone and the CSR results from melting of ice crystals as they fall from generating cells through 0°C level to intensify reflection and scattering of electromagnetic waves, this is only a presumption for formation of the CSR and the DEE. In addition, shapes and sizes of the ice crystals, liquid water content in melting zone and others also have influence on inhomogeneous structure in the bright band, An appropriate combination of these factors may also form the CSR and the DEE. Because of the large thickness of bright band in mei-yu frontal cloud system, the liquid water content can play an important role in formation of the CSR as a result of growth of melting particles by coalescence.

III. PRECIPITATION FEATURES OF STRATIFORM CLOUD IN MEI-YU FRONTAL CLOUD SYSTEM

From the above mentioned echo structure of stratiform cloud is nonuniform in mei-yu frontal cloud system in the southern China. But what is precipitation features of it? Particularly, it is worthy of noting whether precipitation pattern of stratiform cloud can be affected by the CSR and the DEE.

Fig. 7 shows the variations of precipitation intensity with time in a precipitation process obtained at two rainfall stations. We can see that the variations of intensity with time are nonuniform and have remarkable fluctuations. The precipitation recorded at Rucun station and Xucun station are from pure stratiform cloud (namely there are no convective cells in it) before 11:50 and 13:20, respectively, but there are still the fluctuations at two stations.

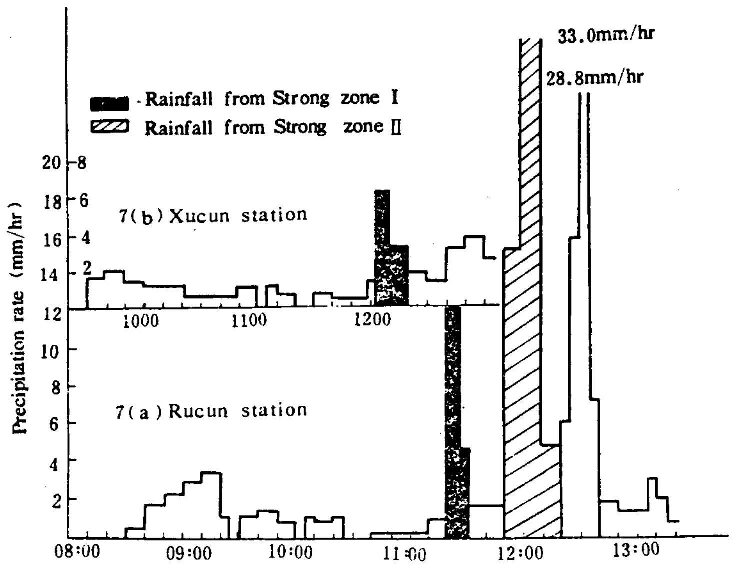

Fig. 7. Variations of precipitation intensity with time in stratiform cloud rainfall at Rucun station(a) and Xucun station (b) on 5 July 1980.

In order to quantitatively analyse precipitation features of stratiform clouds, we divide them into three classes named SI, SII, SIII. SI contains only a few convective cells. Its inhomogeneous structure results principally from the DEE. There are many convetive cells and not obvious bright band in SII.SIII is a pure stratiform cloud with existence of bright band and DEE. We take one precipitation process for SI and SII, and two precipitation processes for SIII; then find average rainfall intensity R_i ($i=1,2,3\cdots n$) in mm/hr within 10 min. from data of rainfall amount at each station. R_i and R_{i+1} can be neglected if $|R_i-R_{i+1}|<2$ mm/hr at two ends of $\{R_i\}$ series for SI and SII, and $|R_i-R_{i+1}|<0.5$ mm/hr for SIII. By using samples $\{R_i\}$ the following quantities can be found.

Maximum rainfall intensity R_{max}: the maximum in $\{R_i\}$, namely $\max\{R_i\}$, Average rainfall intensity $\bar{R}$: $\bar{R}=\sum_{i=1}^{n} R_i/n$,

Maximum difference S among $\{R_i\}$: $S=\max\{R_i\}-\min\{R_i\}$,

Fluctuation amount μ : $\mu=\sigma/\bar{R}$, where $\sigma=[\sum_{i=1}^{n}(R_i-\bar{R})^2/n]^{\frac{1}{2}}$

The parameter values listed in Table 1 are average values for rainfall station (S I and SII) and values for individual station (SIII). Some precipitation parameters of three thunderclouds observed in 1962[3] are also listed in Table 1 for comparison with parameters of the stratiform cloud.

Some features can be seen from Table 1 as follows:

(1) Precipitation pattern is nonuniform. The fluctuation amount μ for SI and SII are 1.14 and 1.17, respectively, it is equal to 0.76 and 1.05 for SIII. But they are 1.12, 2.38 and 1.39 for thundercloud. Obviously, some of μ for stratiform cloud are close to that of weak thunderclound.

(2) Inhomogeneity of precipitation in stratiform cloud is related to inhomogeneous structure of the cloud. Because there are convective cells and strong DEE in SI and SII, μ values are larger. In SIII, which did not contain convective cells, μ values for two precipitation processes are different. In case of strong inhomogeneous bright band and DEE, the μ value is larger, too. Thus, they have an effect on precipitation from stratiform cloud. For example, in stratiform cloud on 18 June 1980, the structure of the bright band is inhomogeneous, but its intensity is weak (~16.0 dbz), the intensity of DEE reached the ground is only 10.0 dbz, R_{max}, $\bar{R}$ and S are equal to 1.8, 0.6 and 1.8 mm/hr respectively. The fluctuation amount (=0.76) is much less than that of SII and SIII. This is not the case with high reflectivity of bright band and the DEE. Stratiform cloud, in which there are the CSR with 30.0 dbz and no convective cells, rained continually for 3 hours at Rucun on 5 July 1980. R_{max} and μ are respectively 7.8 mm/hr and 1.05. These values are no better than those in SI, SII and the thundercloud. It is seen from this that the convective cells snd the DEE can cause larger fluctuations of rainfall intensity in stratiform cloud, and produce shower effect than DEE on precipitation.

(3) The convective cells differ markedly from the DEE in rainfall intensity. In case of stratiform cloud with convective cells, R_{max} and $\bar{R}$ in two precipitation processes are 20.1, 4.5 and 15.8, 3.8 mm/hr, respectively. They are much larger than those of pure stratiform cloud.

Now, further analyses are made for stratiform cloud precipitation on 5 July 1980.

Radar set at Tunxi was 50 km from and to the north of mei-yü frontal line on that day. The observation showed that it was raining from As-Ns and no thunder and lightning occurred. A wide range of stratiform cloud echo was in the range of 50 km from 08:00 to 14:00. From the record of autoraingauge it can be seen that the rain sometime has remarkable shower feature. It resulted from the convective cells and the DEE in stratiform cloud. We select the data of rain from 10:40 to 12:10 at Rucun and Xucun station for analyses.

(1) A brief description of the echo. The rain at Rucun and Xucun station was from a wide spread stratiform cloud moving eastwards. Fig.8 displays partial PPI and RHI echo photographs. Leading edge of the echoes was in the west of radar set and reached to 40 km from the redar at 10:40, and 30, 25 and 10 km at 11:03, 11:09 and 11:45, respectively (Fig. 8a, c and d) . Average moving speed is about 40 km/hr. From Fig. 8 there are several strong echo zones with intensity greater than 10.0 db on the edges and about 15.0—20.0 db in the centre, and free echo zone (black zone with grey echo) of large range. Also shown in Fig.8 is the

Table 1. Some Parameters of Precipitation Fluctuation in Stratiform Cloud

	Stratiform Cloud SI (5 July 1980)	Stratiform Cloud SⅡ (6 July 1980)	Stratiform Cloud Ⅲ		Thundercloud		
			(18 June 1980)	(5 July 1980)			
R_{max}	20.1	15.8	1.8	7.8	44.5	133	47.6
$\bar{R}$	4.5	3.8	0.6	1.7	9.0	12.9	9.9
S	20.1	15.8	1.8	7.8	43.3	133	47.1
σ	5.02	4.33	0.43	1.74	10.1	30.7	13
μ	1.14	1.17	0.76	1.05	1.12	2.38	1.39
n	26.3	25.0	22.0	21.0	16	17	13
Caption	· a few convective cells, remarkable inhomogeneous bright band and high reflectivity cores (30 dbz) · average values for 6 rainfall stations, $\mu_{max}=1.42$, $\mu_{min}=1.00$, 60% of μ are about 1.1	· many convective cells, reflectivity cores with 19 dbz, but no remarkable bright band · average values for 14 stations, $\mu_{max}=1.75$, $\mu_{min}=0.83$, 50% of μ range from 1.1 to 1.3	· low reflectivity (16 dbz) in bright band, · values for individual station (at Rucun)	· strong inhomogeneous bright band · values for individual station (at Rucun)	· from data observed at Taishan Mountain and Hengshan Mountain in 1962 · [3] · values for individual station		

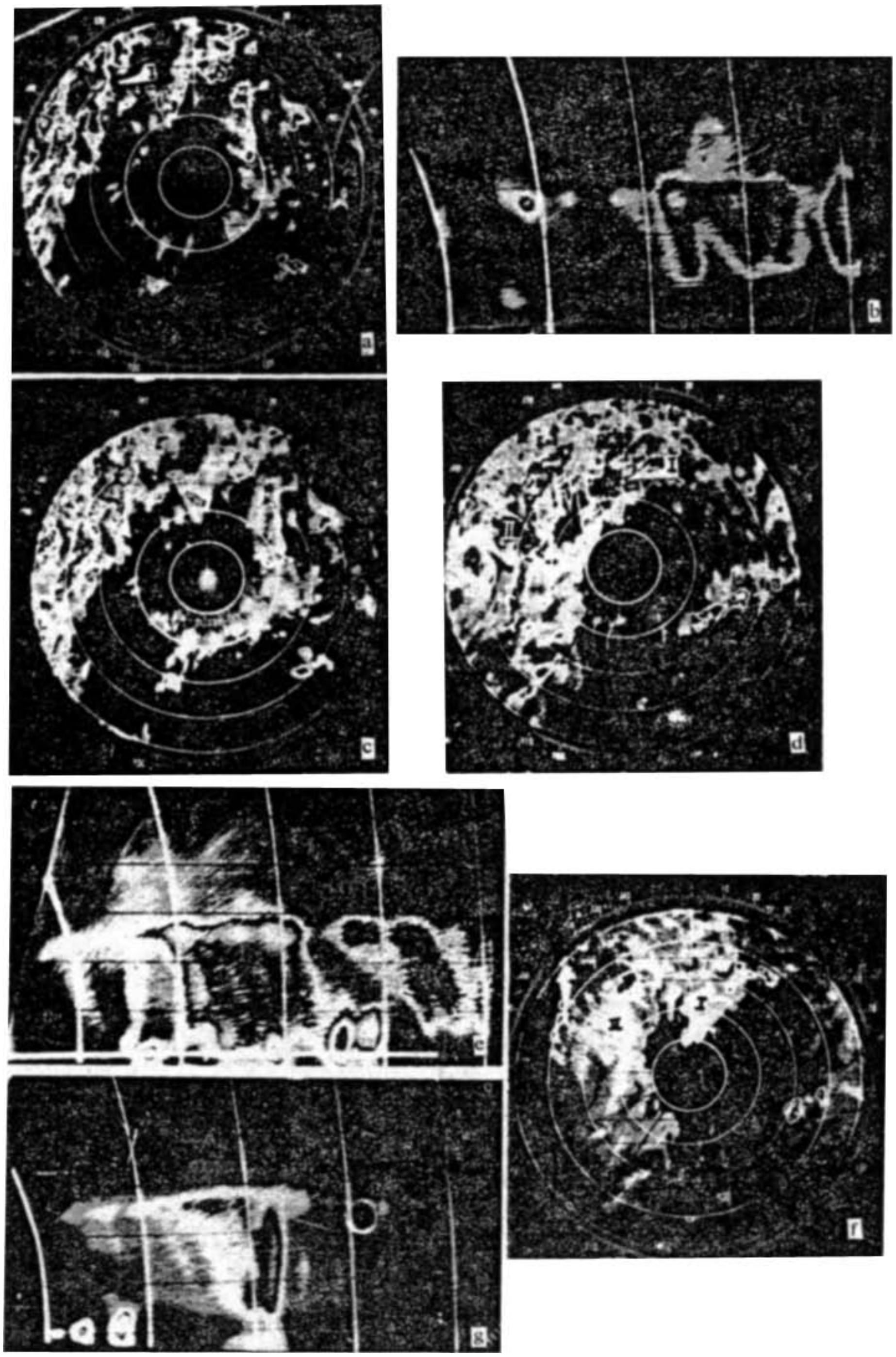

Fig. 8. Some PPI and PHI echo photographs of stratiform cloud which was moving eastwards on 5 July 1980.
(a) 11:03, 5° elevation; (b) 11:05, 305° azimuth;
(c) 11:09, 5° elevation; (d) 11:45, 5° elevation;
(e) 11:48, 011° azimuth; (f) 11:59, 5° elevation; 10 db intervals;
(g) 12:01, 325° azimuth, 10 db intervals.

horizontal nonuniformity in structure of stratiform cloud. Of all the strong echoes, strong zone I with the intensity greater than 20.0 db is the largest in area. RHI section at 11:05 (Fig. 8 (b)) demonstrates that it is a DEE from CSR. At 11:09, the echo intensity in the vicinity of Rucun (326° azimuth, 31 km distance) was above 5 db, strong zone I was about 7 km from Rucun. It was moving at 40 km/hr south-east by east and reached to Rucun station at about 11:20. In moving echoes, the strong zone I reached to the range between 20 and 30 km to the north or the radar set at 11:45 and then free echo zone to the south-west of the radar set can be still seen. The leading edge of zone I approached Xucun station (11° azimuth, 30 km distance). Fig. 8 shows a vertical RHI section along the azimuth of 11° at 11:48. It may be seen that in bright band there are three reflectivity cores from which DEE forms a wide precipitation echo zone because of short range between the cores. In addition, there was a strong zone II with largest area in range from 30 to 40 km behind strong zone I. Its edge reached Rucun station. The Zone II contains a convective cell with horizontal size of about 5 km and top as high as that of stratiform cloud (see Fig. 8g), the remainder of Zone II is DEE. At 11:59 (Fig. 8f), Rucun station was covered with the echo with 20 db of the convective cell and the echo of 30 db was moving to the station.

(2) Precipitation. Fig. 7 illustrates the variations of rainfall rates with time at Rucun station (Fig. 7(a)) and Xucun station (Fig. 7 (b)). As mentioned above, strong zones I and II arrived at Rucun at 11:20 and 11:45, respectively. They are consistent in time with the rain observed at this station at 11:20 to 11:30 and around 12:00. It is clear that the DEE corresponding to the CSR can yield rainfall of 5—12 mm/hr in intensity (for example, rain from strong zone I and II) but rainfall rates around DEE are lower. Therefore, shower rainfall occurred somewhere as the DEE moved through. The convective cells embedded in the stratiform cloud may produce rain with higher rate, although reflectivity and size are not as high and large as isolated cells. Maximum rainfall rate was 33.0 mm/hr at Rucun station when stronger zone II passed through. It was time to rain in the highest rate when convective cell in stronger zone II reached Rucun (Fig. 8f). Consequently, the rain with the highest rate lasting for 10 min. was from the convective cell.

IV. SUMMARY

The structure of stratiform cloud in mei-yü frontal cloud system is often inhomogeneous. Convective cells embedded in stratiform cloud, cores with high reflectivity and DEE from the bright band are major reasons for the inhomogeneous structure. The DEE which has a close relation with inhomogeneity of the bright band is a significant feature of echo structure in mei-yü frontal cloud system. Either the convective cells or the DEE can cause nonuniform distribution in time and space of precipitation from stratiform cloud. The calculation indicates that average rainfall rate within 10 min. is 15—20 mm/hr and fluctuation amount of rainfall rate (~ 1.1) is approximately equal to that of weak thundercloud for stratiform cloud in which convective cells are contained. For pure stratiform cloud, the bright band with obvious inhomogeneous structure and strong DEE can also make the precipitation pattern inhomogeneous. Sometimes the rainfall rate is above 10 mm/hr and fluctuation amount of rainfall rate can reach 1.05.

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