ESTIMATION OF ARTIFICIAL PRECIPITATION ENHANCEMENT RESOURCE CONDITION AND CLOUD SEEDING POTENTIAL BY GROUND -BASED REMOTE SENSING DATA*

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ABSTRACT

In this paper, the data of continuous atmospheric vertical integral vapour and liquid water content during April — June of 1992 — 1994 obtained by a ground-based dual-channel microwave radiometer are used to analyse the statistical characteristics of atmospheric vapour and liquid water content, and the relative distribution characteristics of vapour and liquid water content in cloudy atmosphere, the correlative relation of integral liquid water content L and ground precipitation intensity I, and precipitation transform rate of precipitation system. Finally, the weather modification condition of precipitus stratiform clouds and seeding potential is analyzed and discussed.

Key words: ground-based remote-sensing, artificial precipitation enhancement, resource condition, seeding potential

I. INTRODUCTION

The method of using ground-based microwave remote-sensing to detect atmospheric vapour and liquid water distribution was originated from the United States of America in the early 1980. Hill (1982) reported his results of using microwave radiometer to monitor cloud water distribution characteristics. Heggli et al. (1987) successively monitored the liquid water distribution characteristics of winter storm cloud system in western USA with microwave radiometer. Super and Holrogdl (1985) reported their results of super cooled liquid water in Colorado cloud with microwave radiometer. In 1988, Warner made comparison between results of liquid water content by microwave radiometer and the results by airborne particle measurement system (PMS) and obtained the comparison data. With the aid of microwave radiometer, Long and Huggins (1992) studied the super cooled liquid water in Australia winter storm and precipitation enhancement opportunities

China started atmospheric microwave remote-sensing research and design of radiometer in the late 1970s. In 1980, Zhao (1980) et al. discussed the relevant theory

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and the preliminary results of field experiment. Zhou (1982) demonstrated the theory and method of atmospheric remote-sensing. In the late 1980, China produced its own microwave radiometer and put into field experiment use. Zhao (1991) released his report on comparison between the results of atmospheric vapour and liquid water by radio sounding and the results using ground-based dual-channel radiometer. Nevertheless, by far, there are few works on using microwave radiometer to successively monitor cloud and water distribution and systematic research on cloud water resource condition and weather modification potential. From April to June in 1992—1994, using the new generation dual channel ground-based microwave radiometer made by Peking University, the comparatively systematic observational study was conducted in Hebei Province airplane artificial precipitation enhancement field experiments. The instrument property and atmospheric integral vapour and liquid water retrieval method were reported by reference (Hu et al. 1994; Zhu et al. 1994). Duan et al. (1996) and Wu et al. (1996) studied their distribution and evolution under different atmospheric conditions in Hebei Province. Furthermore, You et al. (1994) used the observational data in Beijing by dual-channel microwave radiometer made by Chinese Academy of Meteorological Sciences, combining the cloud liquid water content data detected by airplane PMS, it discussed the conversion efficiency of cloud water to precipitation and studied cloud seeding resource condition and seeding potential. Based on the preceding work, this paper further discusses the statistical characteristics of atmospheric vapour and liquid water, the correlation between cloudy atmosphere vertical integral water content and rainfall intensity, the rainfall conversion efficiency. This paper also discusses the issues of stratiform cloud water resource conditions for artificial precipitation enhancement and the cloud-seeding potential.

II. DATA COLLECTING

The basic data of this research are obtained by dual-channel co-antenna ground-based radiometer in Shijiazhuang, Cangzhou, Gucheng of Hebei Province from April to June of 1992 to 1994. In the observational period, the microwave radiometer was installed at the above three sites. In order to get the continuous data of vapour liquid water in cloud, from 1993 to 1994, when rain occurred, a parachute-like cover was put on microwave radiometer to use 45° angle observation method. The information of atmospheric vapour, liquid water brightness temperature was put into the indoor computer system through cable, so as to obtain the real time atmospheric vapour, liquid water continuous data. During the three year observation period, total 744 h vapour observation data are obtained, which are under the condition of clear, cloudy and rainy. The cloudy and rainy data are 589 hours. The related data collected is the following (Table 1).

Table 1. Information of Atmospheric Vapour, Liquid Water Data Obtained by Microwave Radiometer

Weather condition	Data sample (h)	Sample content
clear	145	vapour data
cloudy	534	vapour and liquid water data
rainy	55	vapour and liquid water data

In order to study the structure, precipitation characteristics and evolution of precipitus stratiform cloud, airplane, satellite, radar and intensified radiosonde observations were also conducted in the same period, and the rainfall data in the corresponding period were collected as well.

III. THE STATISTICAL CHARACTERISTICS OF ATMOSPHERIC VAPOUR AND LIQUID WATER CONTENT

1. *The Frequency Distribution of Water Vapour Content*

Using the continuous data by dual-channel microwave radiometer from April to June of 1992 — 1994, we make statistical analysis of vapour evolution feature under clear, cloudy and rainy circumstances. The results are shown in Fig. 1 and Table 2.

We can see from Fig. 1 and Table 2 that the median increases as month progresses. Under the same weather condition, the median generally increases 30% — 40%. In the same month period, according to three weather conditions of clear, cloudy and rainy, the integral vapour content median also increases 30% — 40%. The analysis indicates that from April to June, the atmospheric integral vapour increases, this is mainly because the weather system increases and upward motion becomes more and more intensive. When there is weather system, the upper air current transport vapour and lower convection transport vapour upward result in the increase of integral vapour water content when there is weather system in which the precipitation may occur. From this point, we can see that the change of season and weather condition are main reasons for the variation of atmospheric vapour water content.

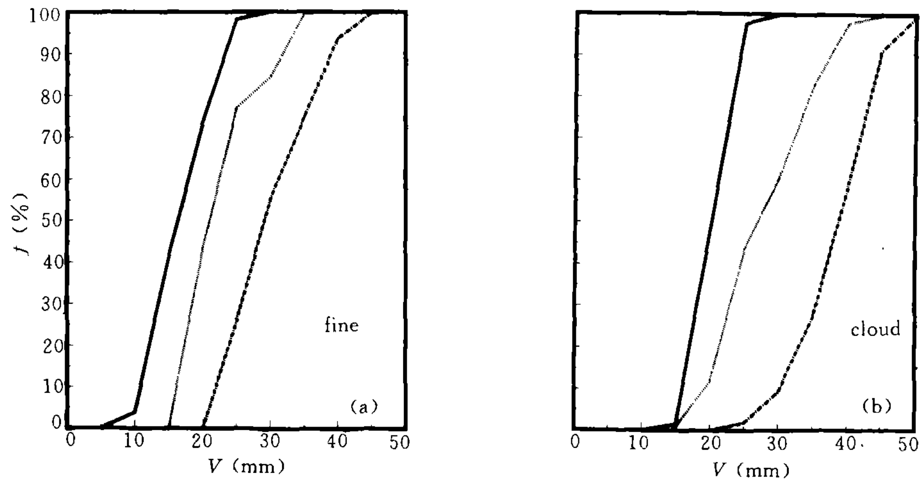
Table 2. Water Vapour Content Median of Different Month and Weather Condition

Weather condition	Water vapour content median (mm)		
	April	May	June
clear	15.6	20.3	28.5
cloudy	20.1	28.2	37.9
rainy	30.4	36.5	51.5

2. *The Frequency Distribution of Liquid Water Content*

Based on the atmospheric stratiform cloud system integral liquid water data by the microwave radiometer continuous measurements from April to June, according to two weather conditions of rainy and not rainy on ground, we make statistical analysis of the monthly variation of cloudy integral liquid water content L. The result is shown in Fig. 2.

The analysis of Fig. 2 indicates that generally speaking in precipitable stratiform cloud, when the cloudy integral liquid water content L is larger than 0.3 mm, it will rain. Therefore we can take the ground microwave radiometer real time observational $L=0.3$ mm as a criterion of whether the stratiform cloud will rain. The statistics shows that L has a comparatively good linear correlation with rain intensity. This conclusion agrees with Zhu et al. (1994) which is based on real time observational L and the ground rain



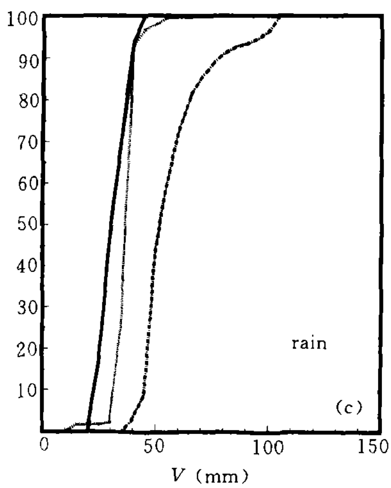


Fig. 1. The frequency distribution of integral water vapour content V (solid line is for April, dot line for May, dashed line for June).

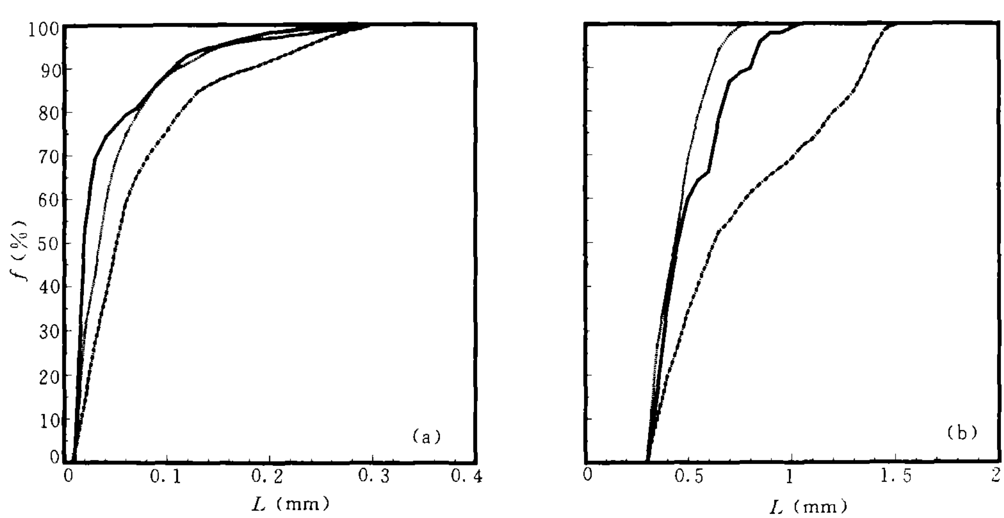


Fig. 2. The frequency distribution of integral liquid water L in (a) cloudy and (b) rainy weather conditions. (solid line is for April, dot line for May, dashed line for June).

intensity evolution data relation. Furthermore, Fig. 2 shows that under the cloudy condition, the variation of cloudy integral liquid water content L is 0. 01 — 0. 03 mm. L increases with month number, April is 0. 02 mm, May 0. 04 mm, June 0. 05 mm respectively. Obviously, the reason for L in May and June is larger than that of April is also due to the fact that the intensity of weather system becomes stronger with month number, whereas the weather system in April is weaker than that of May and June, so cloudy integral liquid water content L is lower.

Figure 2 shows that under rainy condition, L in April is 0. 3 — 1. 0 mm, median is 0. 45 mm; L in May is 0. 3 — 0. 8 mm, median is 0. 44 mm; L in June is 0. 3 — 1. 5 mm, median is 0. 64 mm; As for L median, the difference of April and May is not large, but it is higher in June. This is mainly because the more unstable weather occurs in June. In fact, in June, the precipitable stratiform cloud has many unstable structures, convection increases, condensed water in cloud increases. So the L in June is obviously higher than that of April and May.

IV. THE CORRELATION OF CLOUD VERTICAL INTEGRAL LIQUID WATER AND GROUND RAIN INTENSITY

Based on the continuous microwave radiometer observational data of cloud vertical integral liquid water content L and ground rain intensity I, we can find that L and I have the approximate linear correlation: $L = A + BI$. The L and I of June 11, 1993 and other three tests were analyzed, the fitting results are shown in Fig. 3 and Table 3.

Table 3. The Fitting Coefficient Parameters of L and I of Some Rainy Systems

Rain date (a-mon-d)	A	B	Correlation coefficient
93-06-01	0. 269256	0. 284176	0. 91168
93-06-27	0. 254326	0. 393568	0. 86712
93-06-28	0. 20841	0. 246301	0. 97458
94-06-25	0. 554592	0. 126348	0. 9692

Comparing Table 3 and Fig. 3, we can find that the precipitable stratiform cloud vertical integral liquid water content L has a good positive correlation with ground rain intensity I. When L increases, I also increases; L decreases, I decreases. In the fitting of $L = A + BI$, A actually represents the threshold for starting rain on the ground. Combining with the corresponding cloud structure and rain evolution in raining system, we can find that the value of A is connected with the vertical disposition of clouds in rainy system. When there is strong natural seeder cloud dropping rain participle in the higher layer and there is feeder cloud in the lower layer, cloud water is easily converted to rain, and the threshold of L for raining on the ground is probably small. When there is no natural seeder cloud in the higher layer, although there is good cloud water condition in the lower layer, the formation of rain is difficult, so L will be larger for rain occurring.

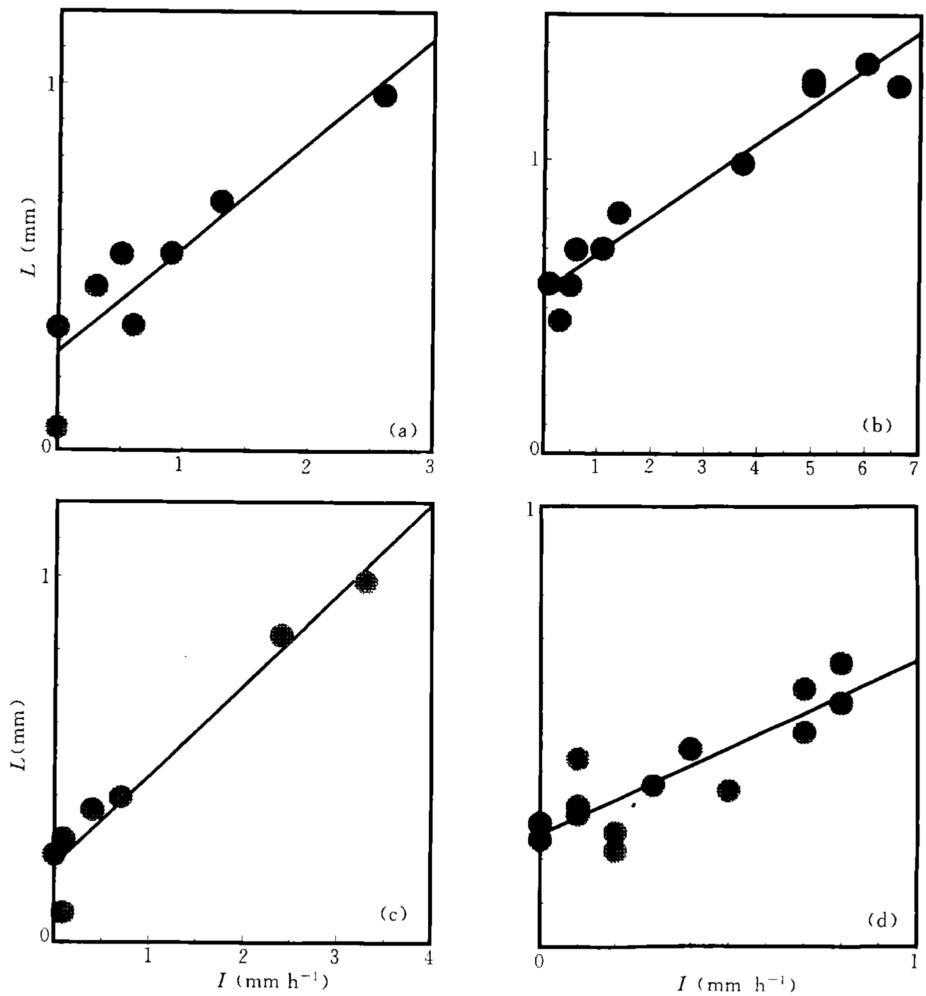


Fig. 3. Fitting relation of cloud liquid water L (unit: mm) and rain intensity I (unit: mm h^{-1}). (a) $L = 0.2693 + 0.2842I$, $n=8$, $r=0.9117$, date: June 11, 1993; (b) $L=0.5546+0.1263I$, $n=11$, $r=0.9692$, date: June 25, 1994; (c) $L=0.2084+0.2463I$, $n=7$, $r=0.97458$, date: June 27, 1993; (d) $L=0.2543+0.3957I$, $n=14$, $r=0.8671$, date: June 28, 1993.

V. THE ANALYSIS OF CLOUD WATER RESOURCE CONDITION AND LIQUID WATER EVOLUTION

1. *Cloud Water Resource Condition*

The water in atmosphere basically exists in gaseous phase which can not form rain directly. From the point of cloud seeding, it is regarded that the resource condition of cloud seeding is the liquid water which is also not converted to rain. For this reason, the amount of atmospheric vapour content can not reflect the resource condition of cloud seeding. So it is important to have a knowledge about the relative distribution of atmospheric vapour and liquid water under cloudy condition.

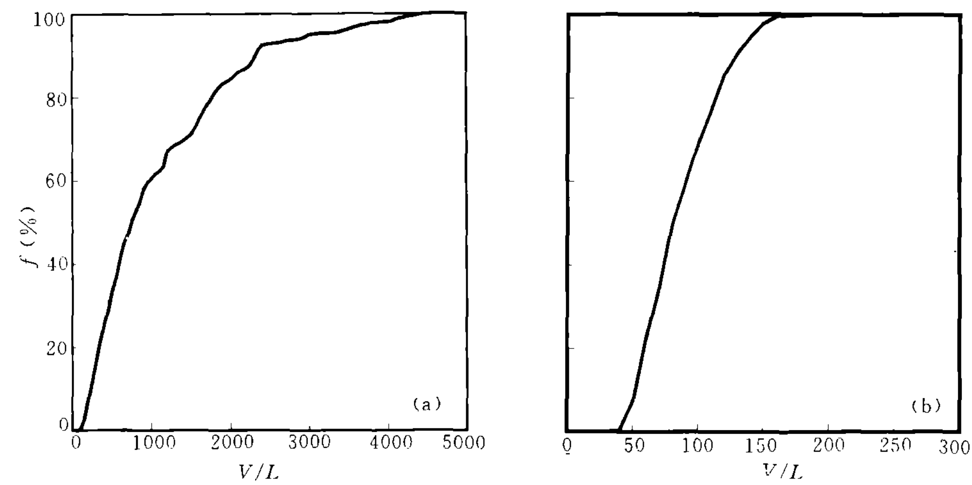


Fig. 4. The ratio of water vapour to liquid water (V/L) under cloudy condition (a), and under rainy condition (b).

Figure 4 shows the ratio of atmospheric vertical integral vapour to liquid water (V/L) from April to June of 1992 — 1994 under rainy and cloudy conditions. The data were obtained by dual channel microwave radiometer continuous observation. When it is cloudy, the ratio of vapour to liquid water (V/L) is generally 100—4000, median is 750, indicating that the amount of liquid water in atmospheric water is less than 1%; whereas it rains, the ratio of vapour to liquid water (V/L) is generally 50 — 150, median is 80, indicating that the amount of liquid water in the total atmospheric water is less than 2%. For two weather conditions stated above, the available liquid water resource for cloud seeding is only a small fraction of the water vapour content in atmosphere.

2. *The Evolution Feature of Liquid Water in Cloud*

Figure 5 represents the time cross section of cloud field during 10—11 June, 1993, when a westerly trough passed by. It is depicted based on the intensified radiosonde observation data, satellite pictures and radar data. In order to analyse the connection between the cloud liquid water content and ground rain, the evolution of L of June 11 observed continuously by microwave radiometer was given below the figure, the ground rain intensity is also given.

From the evolution of integral liquid water content of this weather process measured by the microwave radiometer, we can see that before 0900 BT June 11, the observational station was in front of the weather system, cloud condition was bad, cloud liquid water content was low and below 0.1 mm, there was no rain on the ground. As the system developed, the cloud thickened, the liquid water content also gradually increased. From eleven, L began to increase, at about 1500 BT, liquid water content was more than 1 mm, the corresponding ground rain intensity increased to 2 mm h^{-1} gradually. Later, L decreased, about 1 h later, L increased again, the second maximum appeared, the averaged L approached 0.6 mm, after 1830 BT, the weather system passed through the observational station, the liquid water content dropped under 0.1 mm again.

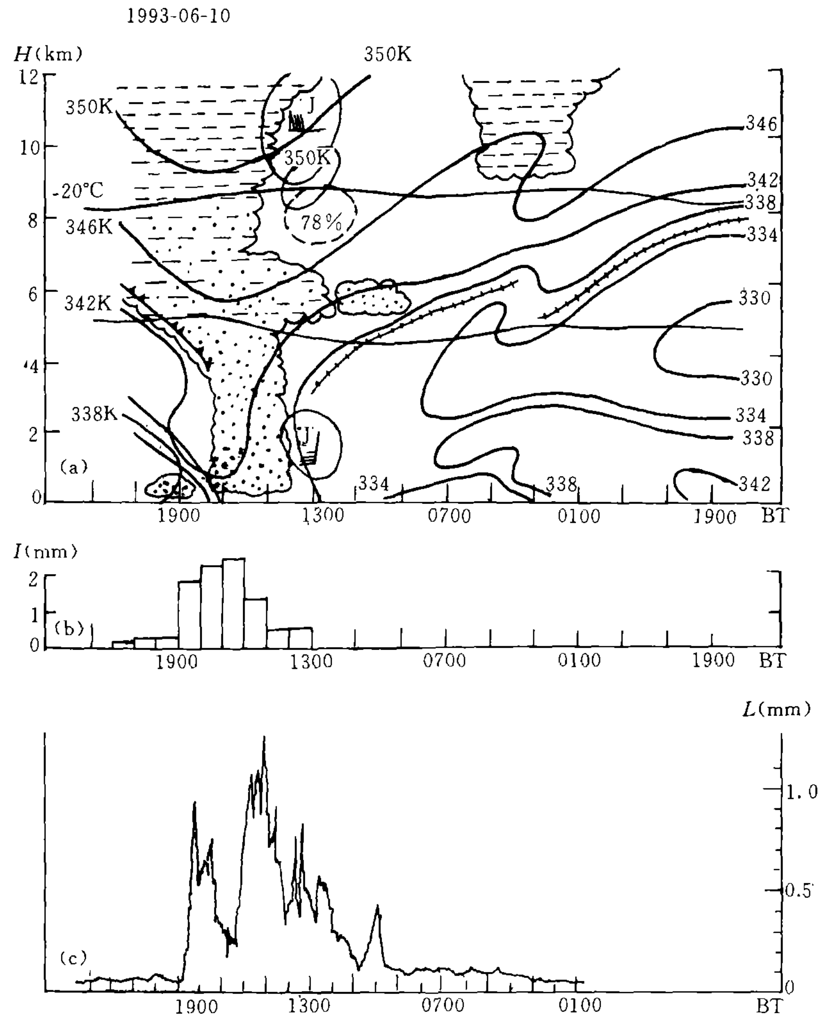


Fig. 5. Time-height cross section of cloud field structure. (a) Isotherm and iso-θ_{se} line. The area enclosed by saw bold lines is high level stable layer. J is high wind center. shaded area is cloud area based on relative humidity. airplane measurement and cloud image. (b) Hourly variation of ground rainfall intensity. (c) Temporal variation of liquid water content L observed by microwave radiometer.

From the time-height cross section of sounding. we can see that about 1200 BT June 11. at the height of 5—6 km. the cloud system before trough entered into Hebei Province. The cloud thickness was less than 2 km and cloud liquid water content L was less than 0. 5 mm. Due to the bad cloud condition. ground rain intensity was less than 0. 5 mm h^{-1}. After 1400 BT. the dense cloud before trough entered into Hebei Province. the cloud base was about 200 m high. the top of cloud was higher than 10 km. the cloud condensation water increased. the maximum liquid water content was larger than 1. 25 mm. There was good natural seeding cloud at higher level and good feeder cloud in mid-level. The situation was good for rain formation and intensification. and therefore. the ground rain intensity increased to 2.6 mm h^{-1}. After 1800 BT, the mid-level and low-level cloud went away, the front moved away, only high cloud at the top of the front remained, the cloud base was higher than 4 km and there was low cloud below 1 km, the liquid water content decreased to 0.6 mm, rain intensity decreased below 1 mm h^{-1} and rain stopped gradually. It is remarkable that from 1730 BT to 1830 BT there was minimum of L and a maximum of ground rain intensity. This indicates that the raindrop scattering effect does not cause large error of L. The decrease of L is likely to be caused by the increased conversion of cloud water to rain.

From the analysis of Fig. 5, we can find that the continuously measured cloud liquid water content L by microwave radiometer has a good correlation with ground rain intensity, the value of L varies with the variation of weather system. The variation of L not only represents the amount of cloud liquid water, but also can be used to analyse the evolution of precipitable cloud system.

VI. DISCUSSION ABOUT RAIN CONVERSION EFFICIENCY AND CLOUD SEEDING POTENTIAL

The key index of cloud seeding is the conversion efficiency of condensed cloud liquid water to rain. The probability of artificial rain enhancement is determined by cloud water condition in raining cloud. For this reason it is important to quantitatively evaluate the rain conversion efficiency and furthermore the seeding potential of artificial precipitation enhancement. The conversion efficiency of natural rain can be defined as the ratio of cloud liquid water to ground rain by natural process, $E = L_{rain}/L$. Because the microwave radiometer can monitor continuously the liquid water content in vertical air column, only if the rain content of air column in the corresponding time is obtained, the natural rain conversion efficiency can be estimated. The rain water content in air column can be reflected in ground rain intensity and its variation, so it can be referred through ground rain intensity. Based on the airplane observation, the rain content below 0°C increases linearly with the decrease of height (You et al. 1994), so the ground rain intensity can be used to evaluate ground rain water content W ($W = 70I^{0.85}$), and to further evaluate the rain water content L_{rain} in air column and estimate the conversion efficiency of natural rain based on $E = L_{rain}/L$ (You et al. 1994). It is obvious that the computed $L-E$ can denote the potential of cloud seeding, in other words, $1-E$ can be used as a quantitative index of cloud seeding.

Figure 6b gives the fitting relations between the estimated E value (or $1-E$) by ground rain intensity and the I observed by the microwave radiometer in Beijing region. The relation of E (or $1-E$) with I using airplane PMS real monitoring data combined with rain intensity data is given in Fig. 6b (You et al. 1994). Figure 6a is the result of observational data and corresponding rain intensity data analysis in Hebei Province by microwave radiometer. In order to reduce the retrieval error of L caused by large particle scattering, only the data of rain intensity less than 4 mm h^{-1} are used (Drake and Warner 1988). Comparing the two figures, we can see that the results of the two sites are nearly the same. The figure shows that with the increase of rain intensity, the cloud seeding potential decreases. But in most cases of fitting, $1-E$ is larger than 0.5, this shows that in most precipitating stratiform cloud in Hebei Province, the liquid water converted to rain

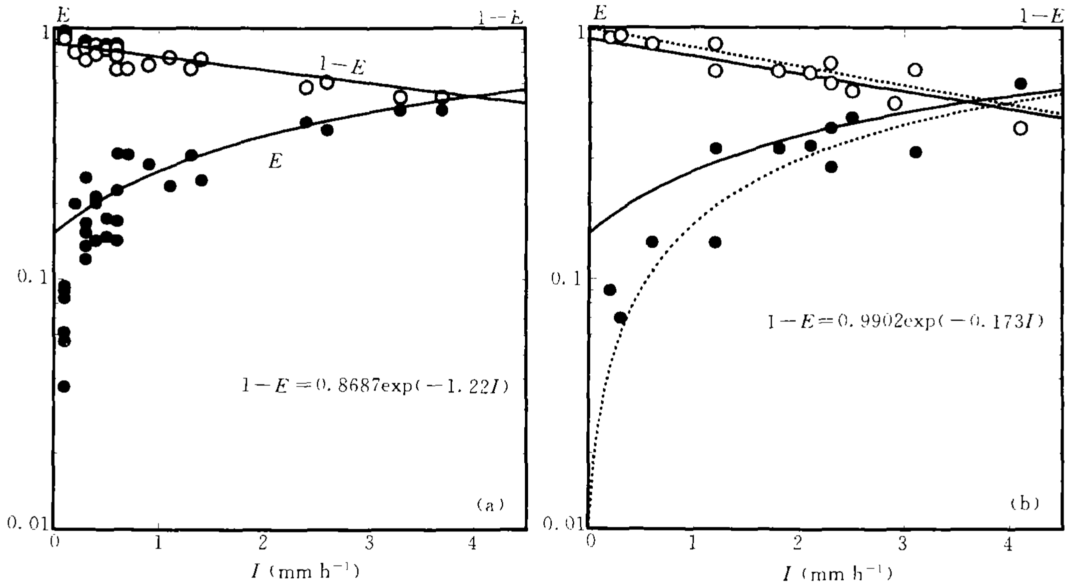


Fig. 6. $E-I$ correlation and $(1-E)-I$ correlation. (a) $1-E=0.8687\exp(-1.22I)$; (b) $1-E=0.9902\exp(-0.173I)$. solid line is observed results by microwave radiometer; dashed line is observed results by airplane.

by natural process is only a small portion. thus it can be regarded that this kind of stratiform cloud has the cloud seeding potential.

It should be noted that the L value of precipitating cloud as measured by microwave radiometer has errors due to the large particle scattering. According to Drake and Warner (1988), this error increases with the increase of rain intensify. When rain intensity is 1 mm h^{-1}, scattering-absorption ratio is less than 10%, when rain intensity is 10 mm h^{-1}, scattering-absorption ratio is 60%. So, Drake and Warner (1988) pointed out that when using radiometer to observe L of precipitating cloud, the acceptable observation upper limit is 1 mm h^{-1}, at most not larger than 5 mm h^{-1}. For this reason, as a test, our research work takes 4 mm h^{-1} as the upper observation limit. The natural rainfall conversion efficiency and cloud seeding potential are analyzed using the observed L by radiometer and rainfall intensity I, the result is reasonable. Nevertheless, in order to make the radiometer observe cloud L more accurately and apply more widely in cloud seeding field, the retrieval problem should be studied thoroughly.

VII. CONCLUSIONS

(1) The analysis indicates that the cloud integral liquid water content L and ground rain intensity I have an approximate linear connection. The formula $L=A+BI$ is used to test the fitting relation with four rainfall events, indicating that they have positive correlation.

(2) Under the same weather condition, the atmospheric integral vapour content median increases 30%−40% (from April to June). In the same month, according to three weather conditions of clear, cloudy and rainy, the integral vapour content median also

increases 30%—40%. This indicates that the changes of season and weather condition are the main reason for atmospheric vapour content variation.

(3) In the precipitating stratiform cloud, when the cloud integral liquid water content L is larger than 0. 3 mm, it will rain. This value can be used as a criterion of whether the stratiform cloud rains or not. When it is cloudy, the range of L is 0. 01—0. 03 mm. The change of median L with month is 0. 02—0. 05 mm. When it is rainy, the range of L is 0. 3 —1. 5 mm. The change of median L with month is 0. 44—0. 64 mm.

(4) The statistical characteristics of V/L under different conditions are analyzed. When it is rainy or cloudy, the ratio of liquid water to atmospheric total water is 1%—2%, showing that the cloud liquid water which is regarded as cloud seeding water resource is only a little part of atmospheric total water content.

(5) Combining the intensive sounding data and ground rainfall data, the evolution of L which is continuously monitored by microwave radiometer is analyzed. The result shows that L increases (decreases) with strengthening (weakening) of the weather system. For this reason, we can know the evolution of raining cloud by analyzing the continuous change of L.

(6) The conversion efficiency of natural rainfall $E = L_{rain}/L$ is analyzed by the observed L and ground layer rainwater content W based on ground rain intensity I and rain water content L_{rain}. The cloud seeding potential $1 - E$ is further assessed. The mathematical connection of $1-E$ and I is constructed by real observational data and it shows that $1-E$ decreases when I increases, that is to say, the relative ability of cloud seeding declines. But in most cases, $1-E$ is larger than 0. 5, this indicates that about 50% liquid water can not converted to rainfall through natural precipitation mechanism. It is therefore concluded that in the cloud under studying there exists the potential of cloud seeding and resource condition for artificial precipitation enhancement.

(7) From our study, we can see that when the rainfall intensity is less than 4 mm, we can use the cloud integral liquid water L observed by microwave radiometer and ground monitored I to study and construct the $(1 - E)$-I and E-I connection, the result is reasonable. Nevertheless, if we want to overcome the error of L caused by large particle scattering under rain or heavy rain condition, we must study the theoretical problem of microwave radiometer data retrieval.

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