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RELATIONSHIP BETWEEN THE VISUAL APPEARANCES OF THAI SUPERCOOLED CONVECTIVE CLOUDS AND THEIR MAXIMUM CLOUD LIQUID WATER CONTENTS

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Abstract: A relationship between the visual "hardness" of a cloud and its maximum cloud water content has been derived for the supercooled convective clouds of Thailand. The measurements were made in 610 clouds over 70 days of cloud studies. The sampling temperatures ranged between -6°C and -10°C. Cloud liquid water was estimated using a Johnson-Williams type hot wire. Cloud hardness was rated several weeks after the cloud flight, using flight video tapes.

The study verifies the common assumption that "harder" clouds have higher cloud water contents. The linear correlation coefficient is 0.75. The potential utility of these results in tropical third-world countries is discussed.

1. INTRODUCTION

In most cloud seeding experiments designed to stimulate the growth of a cloud and its resultant rainfall through the release of fusion heat (commonly called "dynamic seeding") there is a requirement that the top of a supercooled convective cloud have a hard cauliflower appearance to be considered suitable for on-top glaciogenic treatment (Woodley et al., 1982; 1983). The hard cauliflower appearance is believed due to high water contents in small cloud-sized drops (< 50 microns diameter). Once such a cloud is selected visually, it is then penetrated by a seeder aircraft in order to assess its suitability for seeding, where suitability is usually defined as the existence of an updraft and liquid water content exceeding pre-determined thresholds. Seeding normally commences as soon as the threshold values are exceeded and ends when they are no longer met.

The visual cloud selection process is a vital first step in the seeding of supercooled convective clouds, since only a small fraction of a field of clouds is suitable for treatment at any one moment. If the most suitable clouds can be identified visually, it will save a lot of time sampling clouds that do not meet the internal suitability criteria.

Although most cloud seeding practitioners accept the view that a cloud with a hard cauliflower appearance is suitable for seeding, we are not aware of any extensive study relating the visual appearance of a cloud to its internal water measurements. This is done in this paper for supercooled convective clouds in Thailand. A total of 610 cloud passes were made through supercooled convective clouds at temperatures between -6° and -10°C. The median cloud base and penetration-altitude temperatures were 22°C and - 8°C, respectively. The measurements were made on 70 days from late April through September 1991, and the liquid water contents contained in small cloud-sized drops were assessed using a Johnson-Williams type hot wire instrument. Several weeks after each flight, each cloud was rated on "hardness" from video tapes of the flights. The hardness ratings were then compared to the maximum Johnson-Williams cloud water contents measured during the cloud passes.

2. CONTEXT OF THE STUDY

This study was done in the context of the Thailand's national program of weather modification that is coordinated by the Royal Rainmaking Research Development Institute (RRRDI). Since program inception, RRRDI leadership has attempted to improve the effectiveness of their program by taking advantage of the latest scientific findings. In recent years, the program leadership has recognized the need for the development and implementation of a more comprehensive scientific approach to the design, operation, and evaluation of Thailand's weather modification program, which through 1990 involved only warm-cloud seeding. As a consequence, the Royal Thai Government requested assistance of the U.S. Agency for International Development (USAID), which agreed to sponsor a visit by a team of experts to assess the RRRDI program and make suggestions for improvements. This assessment, which was conducted under the auspices of the U.S. Bureau of Reclamation at the request of USAID, was made by four scientists (Silverman, Changnon, Flueck and Lintner). Their assessment and recommendations are contained in a report entitled "Weather Modification Assessment: Kingdom of Thailand" (Silverman et al., 1986).

One of the recommendations of this report is that dynamic seeding concepts be tested in Thailand. This recommendation was accepted and a new, broadly-based program known as the Applied Atmospheric Resources Research Program (AARRP) was established under the auspices of RRRDI. A number of studies have already been conducted in preparation for a demonstration cloud seeding project. These are described in a report by Medina et al. (1989).

After visiting potential experimental sites, officials of the RRRDI and Reclamation selected the

Ping River basin of northwestern Thailand for the conduct of a demonstration project (Figure 1). The Field Operations Center for the 1991 field program was located at the Bhumibol Dam site, and an S-band Doppler weather radar was installed at a site about 9 kilometers southeast of Omkoi on a ridge (height 1,160 m), which provides a good view of the Ping River drainage.

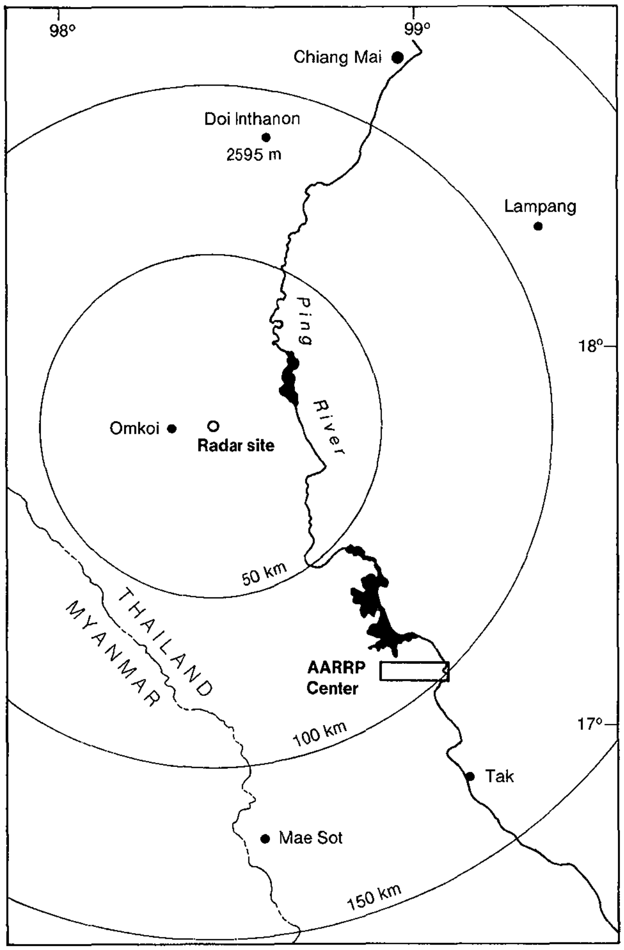


Figure 1. The area of northwest Thailand where the Applied Atmospheric Resources Research Program is being conducted.

The focus of the initial studies is randomized "on-top" seeding of cold clouds using a glaciogenic seeding agent (i.e. silver iodide) at temperatures ranging between -6°C to -10°C to stimulate cloud dynamics through the release of fusion heat. During the analysis phase, the convective cells receiving real or simulated AgI treatment will be tracked on radar using the software of Rosenfeld (1987) and their properties measured in the manner described by Rosenfeld and Woodley (1989).

This randomized seeding effort began in August 1991 and followed the design and procedures specified by Woodley Weather Consultants et al. (1991) prior to commencement. It is patterned after the randomized seeding effort in west Texas described by Rosenfeld and Woodley (1989).

These initial Thai experiments are to be viewed as exploratory in nature. This means that the 1991 field experiment and the subsequent analyses will be a flexible, interactive, guided search for evidence of a treatment effect (Flueck, 1985). Extensive use of data stratifications and partitioning and predictor and covariate variables is anticipated. If the analysis indicates that seeding has affected the precipitation, later experiments can be confirmatory in nature, where a confirmatory experiment is understood to mean a well-defined, inflexible process closely focused on replicating (confirming) a result while minimizing variability and bias (Flueck, 1985). These initial exploratory experiments will serve as the foundation for the Thai demonstration experiment.

3. INSTRUMENTATION AND ITS USE

A turbo-prop Aero Commander 690B aircraft was provided for the AARRP effort under a lease between the Royal Thai Government and Thai Flying Service. This aircraft is equipped with an airborne data acquisition and seeding system, provided by Aero Systems, Inc. of Erie, Colorado, and it is serving as the high altitude seeder/measurement aircraft for the program. In addition to standard avionics and flight instrumentation, this Aero Commander is equipped with the following airborne cloud seeding support instrumentation: a Johnson-Williams type liquid water content meter, a thermo-electric dew point hygrometer, a reverse flow thermometer, a Ball variometer and a satellite-based global positioning system (GPS) that permits location of the aircraft to within 100 m. This GPS navigation system is a major addition to the standard aircraft VOR/DME navigation system because of its increased position accuracies. A forward-looking nose video camera is mounted in the cockpit and provides a continuous view of cloud conditions during flight through the right side of the windshield. Finally, the aircraft is equipped to eject 200 20-gm AgI flares that are loaded into racks, which are mounted on the underbelly of the aircraft forward of its tail. Unfortunately, project resources did not permit the purchase and installation of any in-cloud ice measuring equipment.

Beginning in late April 1991 and extending through mid-October 1991, the Aero Commander was used to reconnoiter supercooled convective clouds in and around the project study area. On three days in August and September, limited randomized cloud seeding operations were conducted according to the procedures specified in Woodley Weather Consultants et al. (1991). All flights were made during daylight hours. Most subject clouds received only one aircraft penetration, because the primary initial objective was to determine the suitability of a field of clouds. In most cases, the hardest cloud within reach of the aircraft at any given time was the one selected for penetration. On some days, especially during June, July and August, it was necessary to fly more than 150 km from the radar in order to find vigorous clouds. All data were recorded on hard disk, transferred to floppy disk at the end of each flight, and then listed in 1 sec intervals.

Our initial intention was to compare a cloud's visual appearance to both its maximum internal water content and updraft speed. Only the former proved feasible, because the updraft speed was not adequately measured. The estimates of cloud drafts from the Ball Variometer are a function of how the aircraft is flown during cloud penetration. If the aircraft is flown at constant attitude, the draft estimates should be fairly accurate. The Thai pilots had virtually no experience in the Aero Commander aircraft and no experience in clouds prior to program commencement, and they were still learning the aircraft through at least half of the summer 1991 effort. By August 1991, however, they had become quite proficient at flight techniques and procedures. Because the draft estimates were of uncertain value, we decided not to use them in this study. Our subjective impression, however, is that there is no relationship whatsoever in Thailand between the speed of an updraft and the visual appearance of the cloud tower that contains the updraft. Strong updrafts were observed in clouds that appeared hard and in clouds that appeared soft prior to entry. This is in contrast to the relationship between cloud appearance and its cloud water content that is the subject of this paper.

4. ANALYSIS PROCEDURES

Three individuals (the two authors plus a third person, usually Mimin Karmini) viewed the video tapes of each flight of the Aero Commander and rated the "hardness" of each cloud tower in nine categories just prior to its penetration. Only the first author had extensive prior experience with convective clouds and their study. The rating ranged from a "soft minus" (i.e. S-), which was assigned a numerical value of 2, to a "hard plus" (i.e. H+), which was assigned a numerical value of 10.

Photographs of clouds exhibiting the entire spectrum of cloud "hardness" are provided in Figure 2. The visual differences are obvious. Note that the towers rated as hard (H) have sharp outlines and hard rounded bubble tops. In contrast, the towers rated as soft (S) have uniform textures with rather indistinct, ragged, irregular edges. Those rated as having medium hardness (M) are somewhere in between. Discerning differences in cloud hardness in some cases was more difficult, accounting for some of the scatter in the derived relationships.

Several problems were encountered during the cloud rating process. These included short viewing time of the subject cloud when the aircraft was in a tight turn to the cloud, poor contrast between the cloud and its surroundings due to a background upper overcast, and limited lighting late in the day. Most of the striking disparities between the cloud hardness rating and its internal cloud water content occurred under such circumstances.

Another factor that undoubtedly contributed to the variability of the results was where the aircraft penetrated the cloud relative to its top. When the aircraft penetrated the rounded growing bubble cloud top above its center, the hardness vs water content comparisons seemed to be best. The comparisons seemed to degrade when the aircraft penetrated the cloud well below the center of its bubble top. In these cases, the aircraft apparently sampled in the bubble wake and not in the active growth region that is most representative of its visual appearance. When this happened, the water content of the cloud was usually less than one might have expected based on its hardness rating.

About 1% of the 610 cloud towers used in this study were seeded after they were rated for hardness and just after the internal water measurements were made. Since seeding took place subsequent to these ratings and measurements, it could not have affected the results of this study.

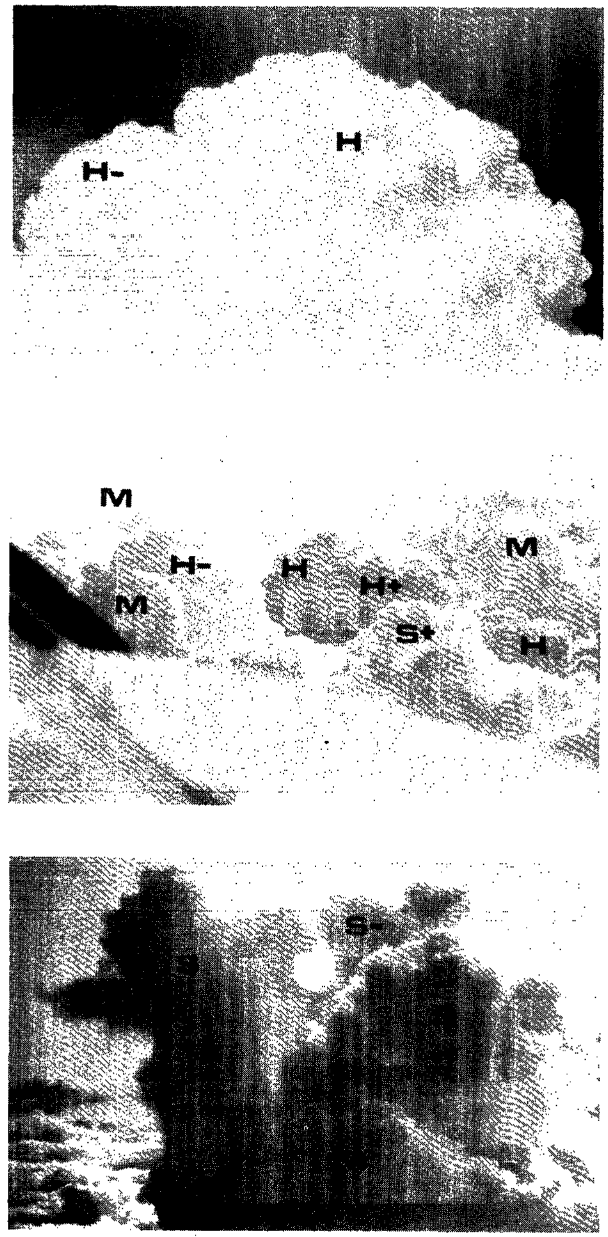


Figure 2. Photographs of supercooled convective clouds with their "hardness" rating superimposed.

5. RESULTS

After each cloud had been rated by three individuals as to its hardness, an average hardness rating was computed, and this average value was plotted versus its corresponding maximum cloud water

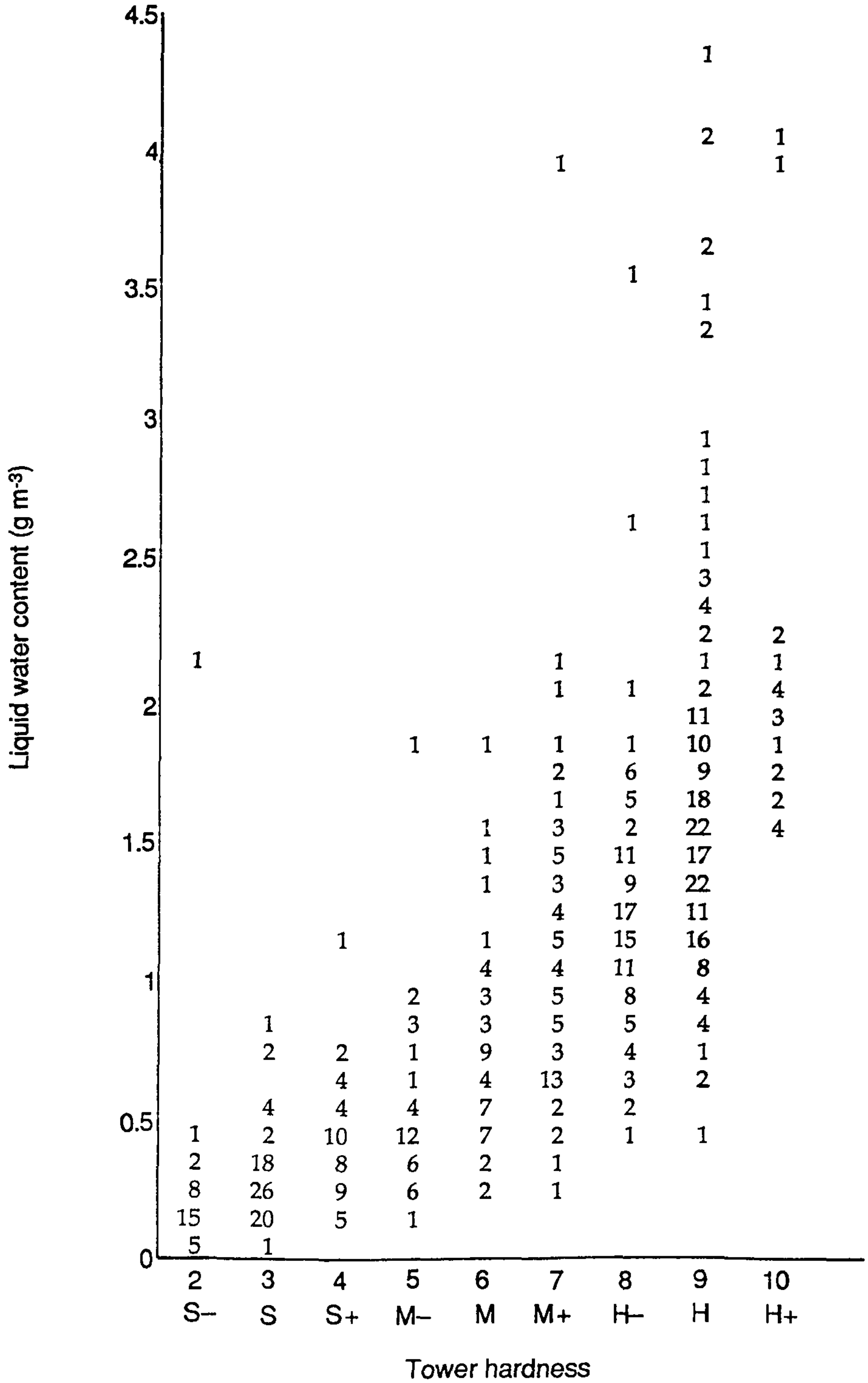


Figure 3. Tower hardness versus maximum cloud liquid water content for April through September. The numbers in the plot refer to the number of observations.

content. This averaging process tended to smooth out the extreme values in the individual ratings and may have improved the correlation between tower hardness and its water content. The results for the April through September period are shown in Figure 3, in which the maximum water contents per hardness class are plotted. Although several outlier values are evident in the plot, a relationship between tower hardness and its cloud water content is evident. The linear correlation coefficient is 0.75.

This analysis was repeated using only the ratings of the first author, who is the most experienced of the three individuals doing the cloud ratings, and the linear correlation between tower hardness and

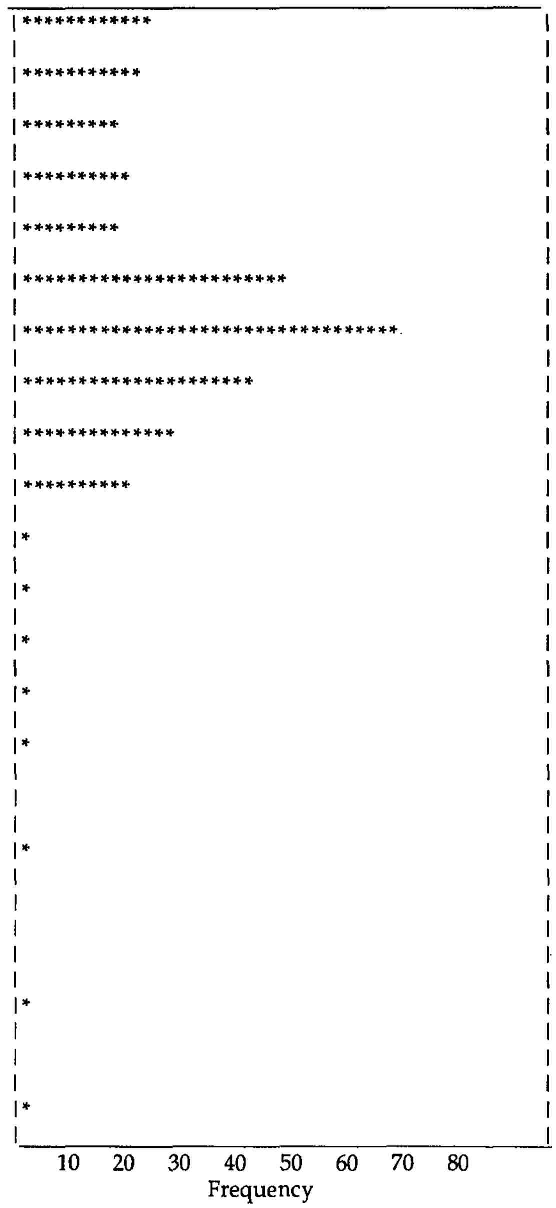
LWC Midpoint		Freq.	Cum. Freq.	Percent	Cum. Percent
0.1	**	87	87	14.26	14.26
0.3	***	81	168	13.28	27.54
0.5	**************************	52	220	8.52	36.07
0.7	*******************	37	257	6.07	42.13
0.9	*********************	42	299	6.89	49.02
1.1	************************************	72	371	11.80	60.82
1.3	**	83	454	13.61	74.43
1.5	****************************	55	509	9.02	83.44
1.7	*******************	37	546	6.07	89.51
1.9	**************	28	574	4.59	94.10
2.1	*****	10	584	1.64	95.74
2.3	***	6	590	0.98	96.72
2.5	**	4	594	0.66	97.38
2.7	*	2	596	0.33	97.70
2.9	*	2	598	0.33	98.03
3.1		0	598	0.00	98.03
3.3	*	2	600	0.33	98.36
3.5	**	4	604	0.66	99.02
3.7		0	604	0.00	99.02
3.9	***	5	609	0.82	99.84
4.1		0	609	0.00	99.84
4.3	*	1	610	0.16	100.00
	10 20 30 40 50 60 70 80 Frequency				

Figure 4. Histogram of cloud liquid water content for April through September.

cloud water content dropped to 0.71. This slight degradation in performance is likely due either to the effect of outlier values that were averaged out in the first analysis or to a case of the students doing better than their teacher.

A histogram of the maximum cloud liquid water contents for each of the 610 passes in the sample is provided in Figure 4. The plot is bimodal with one maximum between 0 and 0.20 gm/m^3 and a second at cloud water values between 1.21 and 1.40 gm/m^3. Note also the few values exceeding 2.5 gm/m^3. It is obvious from this plot that Thai supercooled convective clouds have ample quantities of supercooled liquid water in cloud-sized drops. How much water resides simultaneously in the rainwater is unknown.

Our studies indicate a tendency for the water values and the corresponding hardness ratings in the pre-monsoon (i.e., April and May) and post-monsoon (i.e. September) periods to be higher than those measured during the stronger southwest monsoonal flow (June, July and August). This is quantified in the histogram plots for the two periods in Figures 5 and 6, which are subsets of the data provided in Figure 4, and in Table 1 in which the mean maximum cloud water contents and hardness ratings are tabulated. Note that the mean maximum water content and hardness rating in April, May and September exceed those in the June, July and August period by factors of 1.43 and 1.33, respectively.



LWC Midpoint	Freq.	Cum. Freq.	Percent	Cum. Percent
0.1	23	23	7.28	7.28
0.3	22	45	6.96	14.24
0.5	18	63	5.70	19.94
0.7	19	82	6.01	25.95
0.9	17	99	5.38	31.33
1.1	48	147	15.19	46.52
1.3	68	215	21.52	68.04
1.5	42	257	13.29	81.33
1.7	27	284	8.54	89.87
1.9	20	304	6.33	96.20
2.1	2	306	0.63	96.84
2.3	2	308	0.63	97.47
2.5	1	309	0.32	97.78
2.7	1	310	0.32	98.10
2.9	1	311	0.32	98.42
3.1	0	311	0.00	98.42
3.3	2	313	0.63	99.05
3.5	0	313	0.00	99.05
3.7	0	313	0.00	99.05
3.9	2	315	0.63	99.68
4.1	0	315	0.00	99.68
4.3	1	316	0.32	100.00

Figure 5. Histogram of cloud liquid water content for April, May and September.

This disparity in cloud suitability has a ready meteorological explanation. During light wind regimes in northwest Thailand, as is typical during April, May and September, there is very little orographic cloud and no organized subsidence to the lee of the mountain ridges. The clouds develop in the project area primarily in response to surface heating. When the southwest monsoon flow is stronger, however, virtually all of the study area to the south, southeast and east of the radar is under strong subsidence in the lee of the mountain ridges in extreme eastern Myanmar (Burma). Convective clouds developing in this area are weaker and it takes longer for their updrafts to reach the measurement altitude, providing ample time for the cloud water they are carrying to be converted to precipitation sized drops and/or ice particles before it reaches the sampling altitude. Such clouds will register low water contents on the hot wire instrument, because most of the water cannot be sensed by the instrument, which has an upper limit of about 50 microns. Low cloud water contents also mean a softer appearance in agreement with the hardness ratings.

6. DISCUSSION OF RESULTS

If one accepts the premise that clouds with high cloud water contents are suitable for seeding for dynamic effects, the clouds of northwestern Thailand are quite suitable prior to and after the strong monsoonal flow and less so during the southwest monsoon itself. The results also suggest that it is

LWC Midpoint		Freq.	Cum. Freq.	Percent	Cum. Percent
0.1	********************************	64	64	21.77	21.77
0.3	******************************	59	123	20.07	41.84
0.5	*****************	34	157	11.56	53.40
0.7	*********	18	175	6.12	59.52
0.9	*************	25	200	8.50	68.03
1.1	************	24	224	8.16	76.19
1.3	********	15	239	5.10	81.29
1.5	*******	13	252	4.42	85.71
1.7	*****	10	262	3.40	89.12
1.9	****	8	270	2.72	91.84
2.1	****	8	278	2.72	94.56
2.3	**	4	282	1.36	95.92
2.5	**	3	285	1.02	96.94
2.7	*	1	286	0.34	97.28
2.9	*	1	287	0.34	97.62
3.1		0	287	0.00	97.62
3.3		0	287	0.00	97.62
3.5	**	4	291	1.36	98.98
3.7		0	291	0.00	98.98
3.9	**	3	294	1.02	100.00
4.1		0	294	0.00	100.00
4.3		0	294	0.00	100.00
	10 20 30 40 50 60 70 80 Frequency				

Figure 6. Histogram of cloud liquid water content for June through August.

possible to recognize such suitable clouds visually.

Lamb et al. (1981) indicate, however, that it is really the water content in the precipitation-sized drops that is most important for fusion heat releases, because up to a million cloud water drops must freeze in order to equal the heat output from the freezing of but one rain drop. Although this is true, in the first author's experience a warm-based cloud with only precipitation-sized drops in its supercooled region is usually dying, and it may be too late to have an effect on such clouds.

The best situation for seeding is likely a mix of cloud and precipitation sized water drops, so that when the cloud is seeded the resultant ice crystals can be captured by the rain drops, which then freeze. Although the Aero Commander had no instrumentation to measure droplet sizes, the flight scientists noted at least some rain drops impacting the windshield of the aircraft, even in clouds with high cloud water contents. Such Thai clouds should be highly suitable microphysically for dynamic seeding procedures.

These are the first systematic measurements that have been made in the convective clouds of Southeast Asia. As such, they should be relevant to other areas in the region that have similar climates, including Myanmar (Burma), Viet Nam, Cambodia, Malaysia, Indonesia and the Phillipines. We predict (but cannot prove) that hard supercooled cloud tops in these countries should be indicative of clouds that have dynamic seeding potential. Microphysical

Table 1

STATISTICAL SUMMARY OF CLOUD WATER CONTENT VS CLOUD HARDNESS RATING

April, May and September 1991

Variable	N	Min.	Max.	Mean.	Std. Dev.	Cor. Coeff.
LWC (gm/m^3)	316	0.03	4.29	1.17	0.63	0.74
Tower Hardness	316	2.00	10.00	7.60	2.07	

June, July and August 1991

Variable	N	Min.	Max.	Mean.	Std. Dev.	Cor. Coeff.
LWC (gm/m^3)	294	0.02	3.97	0.82	0.77	0.73
Tower Hardness	294	2.00	9.00	5.70	2.46	

Entire Period (April through September 1991)

Variable	N	Min.	Max.	Mean.	Std. Dev.	Cor. Coeff.
LWC (gm/m^3)	610	0.02	4.29	1.00	0.72	0.75
Tower Hardness	610	2.00	10.00	6.68	2.46	

Note: The hardness values are quantified by the following: Soft minus (2), Soft (3), Soft plus (4), Medium minus (5), Medium (6), Medium plus (7), Hard minus (8), Hard (9) and Hard plus (10).

suitability is, however, only one component of the overall assessment of the suitability of a particular region for seeding. Whether such clouds will, in fact, respond to treatment must still be determined for Thailand and the other counties of the region.

The relationships presented in this paper can be used to provide estimates of the water contents in the supercooled clouds of Southeast Asia. As an example, the results of Figure 3 indicate that there is about a 90% probability that a tropical supercooled cloud rated as "hard" or "hard plus" by a trained person has a liquid water content of at least 1.0 gm/m^3. Armed with this information, a meteorologist in a tropical locale might fly in an aircraft at a flight temperature of about -8^oC and systematically rate the clouds as to their hardness. If this were done over much of a day, an estimate of the number of clouds having a liquid water content of more than 1.0 gm/m^3 could be obtained. Individual convective clouds might be hardness-rated as a function of time to provide an estimate of how long the cloud maintained its high water content. This would give an estimate of how long the clouds of a particular region are suitable for cold cloud seeding. This could be done under various weather regimes. On some days this "seeding window" might be only a few minutes; on others it might be 10 to 15 minutes.

Although certainly not as good as actual cloud penetration and measurement, this would be a relatively simple and inexpensive first step in assessing the cloud water content of supercooled convective clouds in a region. This should be done before a cloud seeding program for rain enhancement is undertaken.

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