PRECIPITATION CHARACTERISTICS OF NATURAL AND SEEDED CUMULUS CLOUDS IN THE ASIR REGION OF SAUDI ARABIA

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ABSTRACT. This study presents the typical meteorological conditions and radar-derived precipitation characteristics of developing cumulus congestus clouds over the Asir region of southwest Saudi Arabia. Radar response variables were analyzed to see if there were differences between clouds seeded using AgI at various stages of development, and carefully selected similar natural clouds that formed nearby and at approximately the same time.

Three groups of seeded clouds were studied: Group I consisted of 28 clouds seeded at a time without any radar echo, and 43 natural clouds for comparison purposes. Group II consisted of 21 clouds seeded when the radar echo was >0 dBZ but <20 dBZ, and 44 natural clouds for comparison purposes. Group III consisted of 13 clouds seeded when the initial radar echo was >30 dBZ, and 19 natural clouds for comparison purposes.

In all three groups, there was a positive association between the seeding and greater maximum radar reflectivity (ZMAX) and maximum precipitation flux (MAX FLUX). The biggest differences between groups was for clouds with ZMAX >50 dBZ and MAX FLUX >100 m^3/s. The greatest seeding effects were observed for clouds that were seeded prior to the appearance of a radar echo. Further research is required to determine the effects on precipitation when seeding clouds that merge with a pre-existing cell.

1. INTRODUCTION

The Kingdom of Saudi Arabia (KSA) has an area of about 2.25 million km^2, most of which is located in arid regions. The available surface water and groundwater resources are limited, precipitation rates are low, and evaporation is high. The Kingdom does not have permanent rivers or significant bodies of water, therefore, rainfall, groundwater, desalinated seawater, and very scarce surface water must supply the country's needs. The vast majority of Saudi Arabia's water needs are met by two sources that are absent in most other countries: water desalination and fossil water. Saudi Arabia is the largest producer of desalinized water in the world, but this is very expensive. Groundwater is stored in more than twenty layered principal and secondary aquifers of different geological ages (MAW 1984). Isotopic analyses show that the fossil groundwater in these aquifers is ten to thirty-two thousand years old. The estimated groundwater reserves to a depth of three hundred metres below ground surface have an estimated total annual recharge rate of 0.13% (Al Alawi and Abdulrazzak 1994; Dabbagh and Abderrahman 1997). The renewable groundwater resources are mainly stored in shallow alluvial aquifers and in basalt layers of varying thickness and width, which are found mostly in the southwest Asir region. These aquifers store about 84 billion cubic metres with an estimated average annual recharge rate of 1.4%. According to the United Nations Environmental Program, the present rate of groundwater withdrawal from the region threatens the Saudi aquifers, and with increased development and population growth, groundwater contamination becomes an additional concern.

Several feasibility studies have been conducted previously in the KSA in order to determine if cloud seeding is able to increase the precipitation. The Saudi Arabia Cloud Physics Experiment (SACPEX) was conducted in 1990 by the University of Wyoming, and they reported a limited potential for provoking significant rain enhancement (Vali 1991). Weather Modification Inc. (WMI) and the National

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Center for Atmospheric Research (NCAR) conducted a feasibility study in 2004 in the southwest Asir region of the KSA, and documented clouds that appeared suitable for hygroscopic and glaciogenic seeding (NCAR 2004). Starting in November 2006, cloud seeding trials and cloud physics research studies have been conducted in Saudi Arabia by WMI for the Presidency of Meteorology and Environment (PME) in both the central region around Riyadh and the southwest Asir region around Abha. The most recent studies have examined cloud and aerosol properties in the two regions to determine if the environmental conditions are favorable for cloud seeding.

Many similar assessment studies have been conducted around the World. For example: in Alberta, Canada (Krauss and Santos 2004), South Africa (Krauss et al. 1987; Hudak and List 1988), the United States (e.g. Dennis *et al.* 1975), Russia (Dovgaluk *et al.* 1991) and Thailand (Woodley *et al.* 2003). The review articles by Bruntjes (1999) and Silverman (2001) discuss the challenges of obtaining the necessary physical evidence, and statistical analyses using unbiased measures to determine sufficient proof that any increases in rainfall were the result of seeding induced causes and effects.

Randomization is the recommended procedure to get statistical seeding results, but natural variability of clouds, especially convective clouds, demands many carefully conducted experiments with no guarantee that there still won't be a bias in sample groups due to natural variability, luck of the draw, or unforeseen circumstances. In many cases, to get statistically significant results one needs to carry out these seeding experiments for many years. Usually, this is difficult to accomplish since most cloud seeding projects are operational in nature. Here, we try to carry out an assessment of seeding results based on data obtained during an operational project, with the latest available radar software, to get statistical results, although the authors clearly understand the inherent shortcomings in this approach.

This paper examines precipitation characteristics of natural clouds and clouds seeded with silver-iodide in the Asir region of Saudi Arabia, and observed by weather radar. A variety of radar derived precipitation parameters have been examined, primarily maximum radar reflectivity, precipitation flux, and rain volume. A summary of the storm characteristics and an exploratory statistical analysis of the response variables are presented.

2. BRIEF CLIMATOLOGY OF THE STUDY REGION

The prevailing climate of the KSA can be classified as hot desert, except in the southwest Asir region. The southwestern Asir region exends from 16.5º to 22º North latitude, and from 40º to 43.5º East longitude. The area is bounded by the Red Sea on the west, and the Najd Plateau and Ar Rub Al Khali desert on the east. The Hijaz plateau bounds the region on the North and the Yemen border to the South.

Rainfall in most of the Kingdom is <200 mm annually, highly irregular with large natural variability and sporadic. The geographic distribution of annual rainfall across Saudi Arabia is shown in Fig. 1 (Ghulam 2007), based on observational data from the PME for the period 1985-2003. Much of the rainfall falls from thunderstorms. The geographic distribution of the annual number of thunderstorm days is shown in Fig. 2 (Ghulam 2007).

The central Kingdom of Saudi Arabia rain season is in the winter and runs from late October through early May and produces an average rainfall of about 110 mm near Riyadh to a maximum of about 250 mm northeast of Qassim during that period. The summer is almost completely dry.

The Asir (southwest) region receives annual rainfall > 300 mm, primarily due to the interaction of the nearby escarpment and the advection of warm, humid conditionally unstable air in the lower atmospheric layer from the Red Sea, a trough of low pressure in Sudan, and the extension of the Indian monsoon low centered over Asia (Abdullah and Al-Mazroui 1998). The precipitation in summer has a strong diurnal cycle due to a sea breeze circulation from the Red Sea and the rapidly rising terrain of the escarpment. The escarpment starts south of Makkah, and consists of a rugged western face with mountains exceeding 2,400 meters in several places with some peaks topping 3,000 meters to the west of Abha. The rugged western face of the escarpment drops steeply to a coastal plain along the Red Sea, whose width averages only sixty-five kilometers. The relatively well-watered and fertile upper slopes and the mountains behind are extensively terraced to allow maximum land use. The eastern slope of the mountain range east of Abha is gentle, melding into a plateau region that drops gradually into the desert Ar Rub al Khali.

The Asir region has a much longer rainfall season, and rain can occur at any month of the year. The mean number of thunderstorm days in the Asir region, over the escarpment west of Abha, is >100 days as shown in Fig. 2, according to Ghulam (2007). March through April are the wettest months of the year, followed by August, December, and January. The driest months of the Asir region are in June, October, and November.

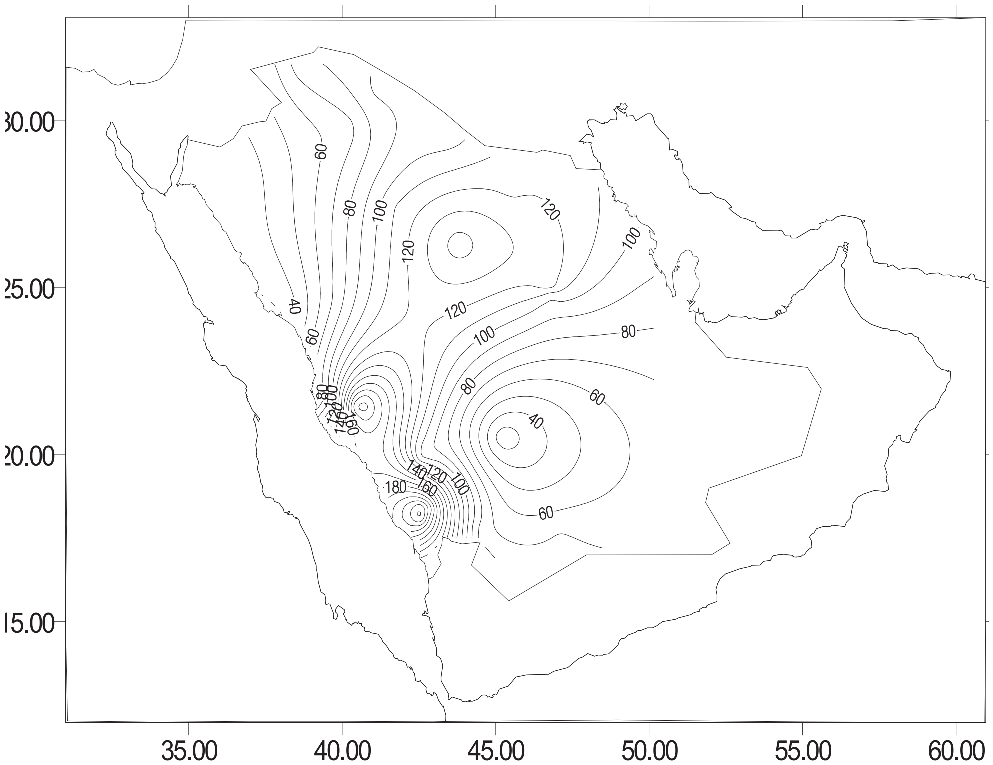

Figure 1: The geographic distribution of annual rainfall (mm) across Saudi Arabia, based on observational data from the PME for the period 1985-2003 (from Ghulam, 2007).

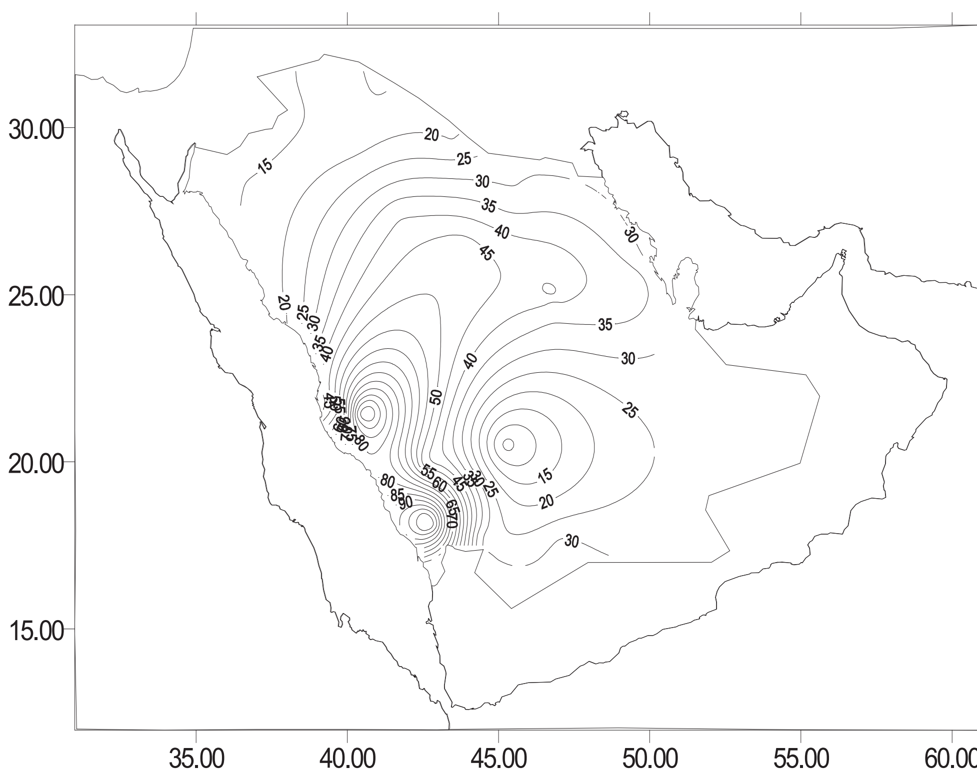

Figure 2: The geographic distribution of the annual number of thunderstorm days (Ghulam 2007).

2.1 Typical Meteorological conditions

A typical atmospheric sounding at Abha during August is shown in Fig. 3. A parcel of air at the surface with temperature 29ºC and dew point 13ºC, produces a lifted condensation level (cloud base) at 4.1 km MSL with temperature 9.5ºC, and CAPE of 2546 J/kg.

The atmosphere is typically conditionally unstable. It is usually very dry above about 6 km MSL due to the presence of a quasi-stationary sub-tropical High. The upper winds are prevailing easterlies. An afternoon southwesterly or westerly wind in the lower atmosphere forms due to a sea breeze circulation between the Red Sea and the escarpment. The sea breeze increases the humidity in the lower atmosphere and triggers or releases the instability, causing tall cumulonimbus clouds to form along the escarpment. All the clouds in this study formed by this process.

Easterly winds prevail at higher levels during the Summer-Autumn period. Hence the sea-breeze convergence zone is enhanced over the escarpment which is an additional dynamic factor for thunderstorm development. Moreover, the directional and speed wind shear with altitude contributes to the formation of long-lived storms and the possibility to form hail (Marwitz 1972, Bibilashvili *et al.* 1981). Hail is a common phenomena during the summer in the Asir region, and the project aircraft of WMI have encountered hail during research and seeding missions.

The lifted condensation level (LCL) can be used to approximate the cloud base level. The distribution of lifted condensation level (LCL) temperatures for all soundings during the month of August 2009 is given in Fig. 4. The mean LCL temperature is 5.9ºC, however, there clearly exists a bi-modal distribution with peaks at approximately 12ºC and another peak near -4ºC. This shows the difference between cloud base height and temperature with and without the presence of the sea breeze. The sea breeze corresponds to the warm, lower cloud bases created by the maritime-tropical air from the Red Sea. Clouds with very low bases with temperatures near 20ºC are sometimes observed in the region. This results in large liquid water contents within clouds and very intense precipitation during some rain events. The higher, cooler cloud bases correspond to air originating from the continental airmass over the interior of the KSA. The clouds in this study formed in the maritime tropical air masses.

The studies by Johnson (1982a, 1982b), based on theoretical calculations and observations for different geographical areas, suggested that the cloud base temperature separating the ice phase and warm-rain-coalescence precipitation formation mechanisms is between 10º and 15ºC. Cloud base temperatures >15ºC had a much greater

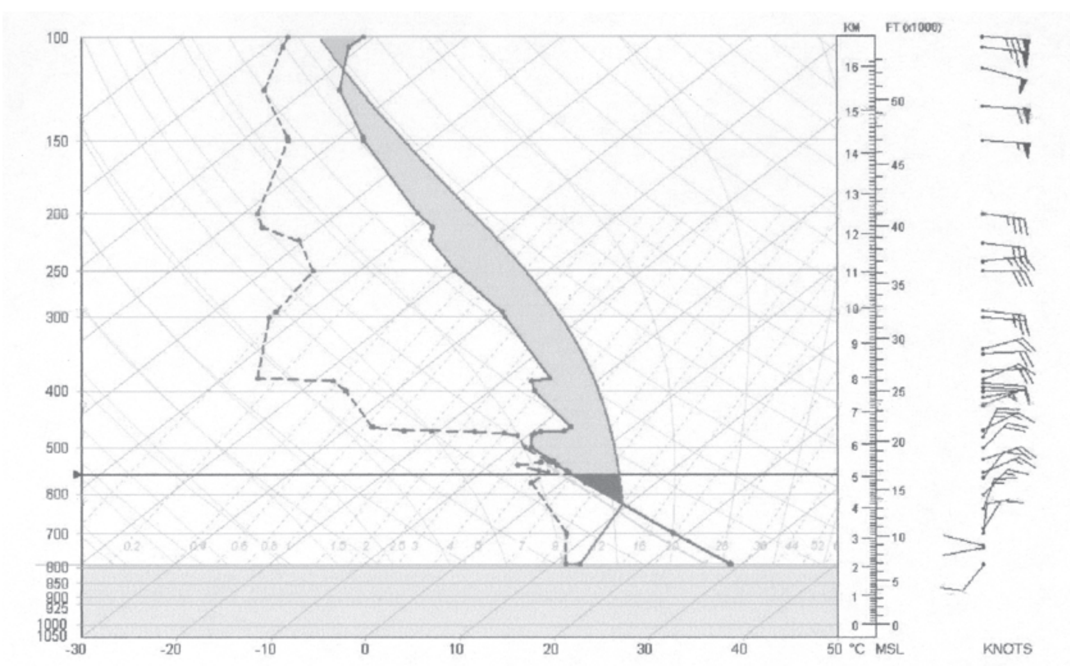

Figure 3: A typical SKEWT vertical profile of temperature, humidity, and wind at Abha on August 17, 2008 at 12Z (1500 local time). The shading represents a CAPE of 2546 J/kg. Cloud base is at 4.1 km and 9.5 C.

propensity to develop precipitation via the liquid coalescence process. The Asir cloud base temperatures are mostly characteristic of continental cumulus clouds. Airborne cloud physics measurements indicate continental type cloud droplet concentrations in the hundreds per cubic centimeter (Vali 1991, NCAR 2008) and an active ice phase precipitation process. However, the role of a liquid coalescence precipitation process and large liquid drops cannot be completely ruled out for cloud base temperatures >15ºC due to an unknown contribution by large aerosol particles, especially for clouds triggered by the warm, moist sea breeze, as discussed by Johnson (1982a and 1982b).

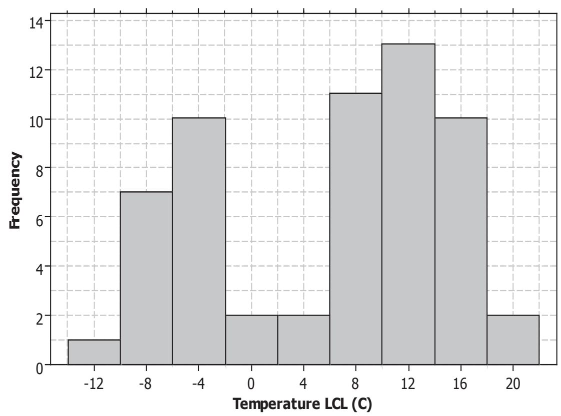

Figure 4: The distribution of lifted condensation level (LCL) temperatures for the month of August 2009 computed using the Abha radiosonde soundings. The bi-modal distribution shows the difference between continental air masses (cold cloud bases) and maritime air masses (warm cloud bases).

3. WEATHER RADAR CHARACTERISTICS

The radar used in this study is located at Abha (18.2286 N, 42.6607 E, elevation 2105 m). It is a C-band (5.35 cm wavelength) radar, manufactured by Gematronik, upgraded in 2008 to include a Vaisala-Sigmet RVP8 signal processor receiver. The nominal output power is 250 kW and the beam width is 0.9 deg. The minimum detectable signal equals approximately 0 dBZ at 100-km. The radar was operated 24 hr per day during the operational period. A complete volume scan was performed every 5 min.

3.1 TITAN Radar Software

The radar data for this study was processed using the software system called TITAN (Thunderstorm, Identification, Tracking, Analysis and Nowcasting). The program ingests radar data, converts it into Cartesian coordinates, identifies storms, tracks them and displays the tracks and forecasts (Dixon and Wiener 1993). TITAN makes it possible to compute a number of relatively sophisticated storm and track parameters very easily in real time and for post analyses (as detailed in Mather *et al.* 1996).

The radar reflectivity data were transformed into rainfall amounts using the Marshall–Palmer (M-P) relationship: $Z = 200R^{1.6}$ where Z is in mm^6/m^3 and R is in mm/h (Marshall and Palmer 1948). To avoid hail contamination, the maximum Z for the rain calculation was truncated at 50 dBZ. The ability of single polarization radar to measure rainfall has been well documented in the literature (e.g., Wilson and Brandes 1979). Empirical values of radar reflectivity vs. rain intensity relations and their variations for geographical location, storm to storm, or even within individual storms, have been the subject of many studies (a list of empirical Z–R relations can be found in Battan 1973). The Marshall and Palmer relation is the most widely used description of the size distribution of raindrops and fits measured raindrop spectra typical for a wide range of rainfalls reasonably well (Joss and Waldvogel 1990). Attempts to optimize Z–R relationships for a specific region between gage and radar estimates have not yielded substantial improvement and are generally not the major issue in radar rainfall measurements (Smith *et al.* 1975). The measurement of raindrop spectra using disdrometers began in the Asir region during August 2009. Ongoing analyses (Kucera, private communication) indicate the Z-R relationship for the Asir region is approximately $Z=300R^{1.44}$. Any differences with the M-P relation are not thought to be significant for the purposes of this paper.

The TITAN system objectively computes cell statistics for all storms within the radar viewing area. This feature allows the comparison of seeded storm cells with many natural (non-seeded) storm cells in an objective manner. The only difference between the seeded and non-seeded cells is their location. Otherwise, the geographical and meteorological conditions were the same.

3.2 Cell Identification and Tracking Criteria

The TITAN package was set to objectively identify and track cells defined by radar reflectivity >30 dBZ, with volume >10 km^3, above 2 km MSL. Furthermore, only storm cells that existed longer than 10 min were chosen to eliminate the very many small cells that pulse up and down for only one or two radar scans, which generally would not be seeded.

4. CLOUD SEEDING METHODOLOGY

Cloud top seeding was conducted by Beechcraft King Air turbo-prop aircraft flying at an altitude corresponding to the -10ºC level, typically between 6 and 7 km MSL. The seeding aircraft penetrate the tops of the developing cumulus towers as they grow through the -10ºC altitude and seed them using 20-g ejectable silver-iodide flares (described at www.ice-flares.com). The flares fall approximately 1200 m during their 37 s burn time. The fall zone covers a temperature range of approximately 8ºC; therefore, the seeding material is dispensed in a vertical curtain covering the temperature range at which the glaciogenic nuclei first become active. The seeding aircraft penetrate the center of single convective cells in most cases. For multi-cell storms, or storms with feeder clouds, the seeding aircraft seed the tops of the developing cumulus towers on the up-wind sides of the more mature convective cells, as they grow up through the -10ºC altitude.

4.1 Seeding Rates and Amounts

The ejectable flares are typically dropped at a rate of one 20-g flare every 5 s (500m) during a cloud penetration. This translates to a seeding rate of approximately 240 g of seeding material per minute. The flares produce $3x10^{13}$ ice nuclei per gram of material at –10ºC, based on cloud chamber tests (Demott 1999). Seeding continued as long as new developing convective clouds with updrafts and super-cooled liquid water were observed during seeding penetrations at approximately 3-5 min intervals. Seeding stopped if there were visual signs of glaciation and high ice concentrations.

5. DATA ANALYSIS

5.1 Cloud Selection Criteria

Several groups of seeded clouds were chosen for the investigation of seeding effects. These were all cumulus congestus clouds; however, the seeding was carried out at different stages of cloud development dependent on proximity of the seeding aircraft to the cloud.

The first group of clouds was seeded without an existing radar echo (minimum detectable signal is approximately 0 dBZ inside 100 km range), but a radar echo formed on the next volume scan (time between scans is 5 minutes). The second group of clouds was seeded when there was a radar echo > 0 dBZ but less than 20 dBZ at time of seeding. The third group of clouds studied was seeded at a stage when a TITAN cell (reflectivity >30 dBZ) had already formed. All clouds chosen for this analysis formed TITAN cells that persisted for more than two radar scans (>10 min of TITAN cell duration).

Naturally developing clouds were chosen for comparison. Clouds were chosen that developed in the close proximity to the seeded clouds in space and time. These clouds were chosen for comparison analysis if they produced a TITAN cell that lasted more than two scans (>10 min duration), similar to the seeded clouds. Their position was within +/- 25 km from the seeded clouds in most cases, though in some cases they were located slightly further. We also tried to choose more or less equal number of naturally developing clouds with the number of seeded clouds, but sometimes there were slight differences on a given day.

Cumulus congestus clouds that merged with larger cells (usually called feeder cells) and further develop as a part of larger thunderstorm complexes, commonly observed in the Asir region, were not included in the first part of the study.

A common criticism in this type of non-randomized study is that the pilots choose the best cloud candidates for seeding, and so there is bias against the naturally developing clouds being initially weaker. In the case of the Asir region, we do not believe this is a problem, and often it is definitely not the case. In many cases the developing convection in the Asir region is so intense that the pilots select less intense, developing clouds due to comfort and safety reasons. Whether a cloud is seeded or not is mostly determined by the proximity of the aircraft to the cloud, at the time the growing cloud top passes through the altitude of the -10ºC level. The authors believe that the seeded clouds are a representative, independent sample of the overall population of clouds, and care was taken to not bias the sampling in any way. In many ways the seeded clouds were selected randomly by the pilots, but not in a formal manner.

6. CHARACTERISTICS OF CONVECTIVE CLOUDS EARLY IN THEIR DEVELOPMENT

A total of 136 single cumulus congestus cells were selected for analysis from 2008 and 2009 in the Asir region, within 100 km range of the Abha radar, during the months of June (9 days), July (9 days), August (15 days), and September (9 days). All clouds under consideration formed due to day-time heating and the sea breeze, between 09:40 and 14:45 UTC. The most intense development was observed between 11:30 and 13:00 UTC (14:30 to 16:00 local time), and 73% of the clouds in this study formed during this period of time

6.1 Clouds Seeded With No Echo

Of the 136 clouds, 28 were seeded when they did not have a radar echo. Forty-three (43) nearby natural clouds were chosen for comparison. All 71 of these clouds produced a radar echo on the next radar scan (5 min later). The time of the previous scan was accepted as the zero time for reference purposes and subsequent analysis.

The radar variables chosen for analysis were maximum radar reflectivity (ZMAX) and maximum precipitation flux (MAX FLUX). The probability plots of ZMAX for the 43 natural and 28 seeded clouds are shown in Fig. 5, and a statistical summary of ZMAX is given in Table 1. The maximum values of ZMAX were in the range from 34 dBZ to 64 dBZ. Figure 5 shows a tendency for seeded clouds to have greater maximum reflectivity in comparison with naturally developing clouds. The 95% confidence intervals for the corresponding normal distributions are also shown in Fig. 5. The Student's t-test was used to test the difference between the means. The assumptions of the t-test are that both groups are independent of one another and that the distributions are normal. The ZMAX values are distributed sufficiently normally (as shown in Fig. 5) to test the difference in the means. The seeded clouds had a mean maximum reflectivity 3.3 dBZ greater than the natural cases and the difference is significant at the 94% level.

The probability plots of MAX FLUX for the natural and seeded clouds are shown in Fig. 6 and a statistical summary of MAX FLUX is included in Table 1. The observed MAX FLUX varied between 7 and 5011 m^3/s. The distribution of MAX FLUX is observed to be log-normal (shown in Fig. 6). There is a tendency for seeded clouds to have greater MAX FLUX in comparison with the natural clouds. The median MAX FLUX for the seeded (S) clouds was 193 m^3/s and 148 m^3/s for naturally (N) developing clouds. The S/N ratio of the median values is 1.3. We have applied the t-test on the log-transformed values to meet the requirement that they have normal distributions with similar variances. The seeded clouds had greater mean MAX FLUX, significant at the 93% level.

Although not statistically significant at the usually accepted level of 95% confidence, there is a strong positive association between the seeding and increases of ZMAX and MAXFLUX.

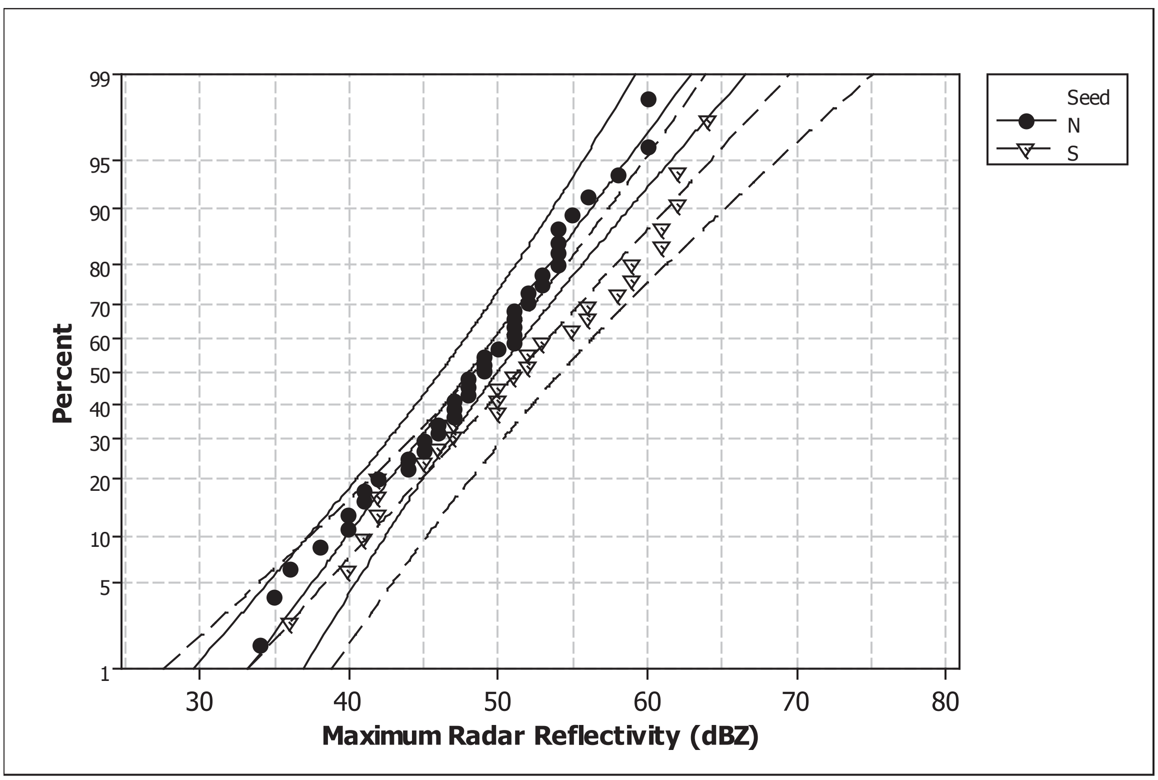

Figure 5: Probability plot of maximum radar reflectivity for 43 natural clouds (N) and 28 seeded clouds (S) that had no-echo at time of selection. The 95% confidence intervals for the corresponding normal distributions are also shown.

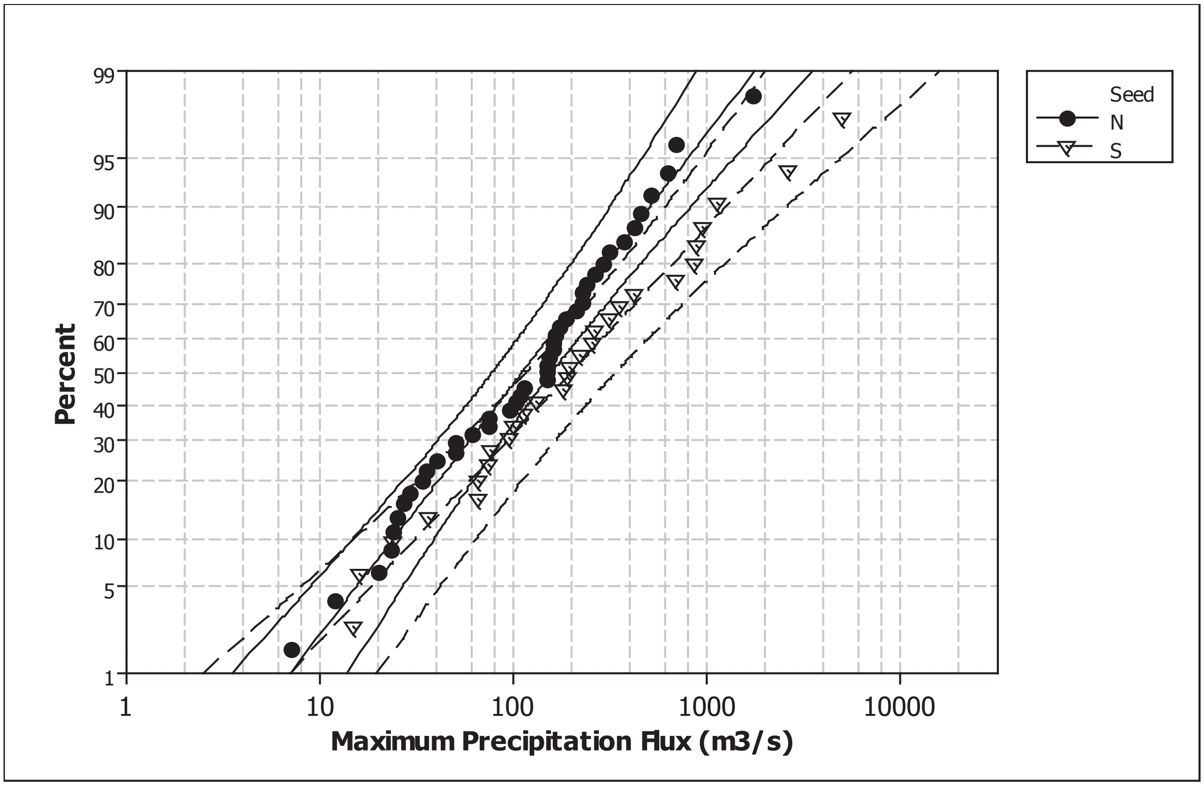

Figure 6: Probability plot of maximum precipitation flux for 43 natural clouds (N) and 28 seeded clouds (S) that had no-echo at time of selection. The 95% confidence intervals for the corresponding log-normal distributions are also shown.

Table 1: A statistical summary of ZMAX, Log MAX FLUX, MAX FLUX, Time to ZMAX, and Time to MAX FLUX for the 43 Natural cells and 28 Seeded cells with no radar echo at time of selection.

Variable	Seed	N	Mean	StDev	Minimum	Q1	Median	Q3	Maximum
Zmax(dBZ)	N	43	48.1	6.4	34.0	44.0	49.0	53.0	60.0
	S	28	51.4	7.8	36.0	45.3	51.5	58.8	64.0
Log Max Flux (m3)	N	43	2.0	0.5	0.8	1.6	2.2	2.4	3.2
	S	28	2.3	0.6	1.2	1.9	2.3	2.8	3.7
Max Flux (m3/s)	N	43	210.2	290.2	7.0	40.0	148.0	239.0	1737.0
	S	28	549.0	1026.0	15.0	74.8	193.0	625.0	5011.0
Time to Zmax	N	43	26.9	11.8	10.0	20.0	25.0	35.0	60.0
(min)	S	28	25.9	10.5	15.0	20.0	25.0	30.0	65.0
Time to Max Flux	N	43	27.9	13.4	10.0	20.0	25.0	35.0	60.0
(min)	S	28	26.1	13.2	15.0	16.3	22.5	30.0	65.0

Another important parameter which can be expected to have changes due to seeding is *Time to reach Maximum Radar Reflectivity.* Time zero for both the natural and seeded cases is 5 min before appearance of the first echo. A statistical summary for *Time to Maximum Radar Reflectivity* and *Time to Maximum Precipitation Flux* is given in Table 1. The mean time to reach ZMAX for the Natural and Seeded groups is 26.9 and 25.9 minutes respectively. The seeded clouds achieved their ZMAX more quickly, but the difference is 1 minute and not statistically significant. The mean time to reach MAX FLUX for the Natural and Seeded groups is 27.9 and 26.1 minutes respectively. The seeded clouds achieved their MAX FLUX more quickly, but the difference is 1.8 minutes and not statistically significant. The median times to reach ZMAX were 25 min in both cases. The third-quartile values of ZMAX and MAX FLUX were 5 min less for the seeded cases. The maximum times of ZMAX and MAX FLUX were 5 min greater for the seeded cases, but this may be due to ZMAX being 4 dBZ greater in the seeded cases, and MAX FLUX was also substantially greater for the seeded cases, therefore, it is reasonable to expect these maximum values to require additional time. Overall, these observations do not indicate any significant differences in times to achieve ZMAX or MAX FLUX.

The *Height of Maximum Reflectivity* at 5, 10, and 15 min was investigated to see if there were differences that could be attributed to seeding, and a statistical summary of the *Heights of Maximum Reflectivity* are given in Table 2.

The heights of maximum reflectivity versus time were very similar for the seeded and natural clouds. These heights correspond to the cloud layer between -10ºC and 0ºC (i.e., melting level). This is consistent with a precipitation formation process involving the ice phase as reported by Vali (1991) and NCAR (2008), for both the seeded and natural clouds, whereby the first precipitation sized particles form near the -10ºC level, and then begin to descend in the cloud. These statistics do not preclude some role of liquid coalescence and large drops, although 15 min is generally insufficient time for coalescence to produce precipitation size drops that could fall in the cloud.

6.2 Clouds Seeded With Radar Reflectivity >0 dBZ but < 20 dBZ.

Twenty-one (21) clouds were seeded when they had a radar echo >0 dBZ but < 20 dBZ. Forty-four (44) nearby natural clouds were chosen for comparison, also with initial radar reflectivity >0 dBZ, but <20 dBZ.

A statistical summary of the initial radar reflectivity (*Zinitial*), ZMAX, and MAX FLUX for the 44 natural cells and 21 seeded cells is given in Table 2. There was a 0.5 dBZ difference in the mean and 2 dBZ difference in the median initial radar reflectivity between groups at the time of seeding, with the seeded group having a slight advantage at the outset.

Table 2: A statistical summary of the Maximum Radar Reflectivity Heights (km) at 5 min, 10 min, and 15 min, for the 43 Natural cells and 28 Seeded cells with no radar echo at time of selection.

Variable	Seed	N	Mean	StDev	Minimum	Q1	Median	Q3	Maximum
HZm(5min), km	N	43	6.8	1.1	4.0	6.0	7.0	8.0	9.2
	S	28	7.0	1.4	4.0	6.0	7.0	8.0	9.0
HZm(10 min), km	N	43	6.2	1.2	4.0	5.4	6.1	7.0	8.0
	S	28	6.3	1.4	4.5	5.1	6.0	7.4	11.0
HZm(15min), km	N	43	5.5	1.5	1.6	4.0	5.5	6.8	8.9
	S	28	5.4	1.8	1.7	4.0	5.7	6.2	10.0

Table 3: A statistical summary of the distribution of initial radar reflectivity, ZMAX, and MAX FLUX for the 44 Natural cells and 21 cells Seeded when the radar reflectivity was >0 dBZ but <20 dBZ.

Variable	Seed	N	Mean	StDev	Minimum	Q1	Median	Q3	Maximum
Zinitial (dBZ)	N	44	11.1	5.4	1.0	6.3	12.0	15.0	20.0
	S	21	11.6	5.8	0.5	7.0	14.0	15.5	20.0
Zmax(dBZ)	N	44	45.9	5.9	35.0	41.5	46.0	50.0	59.0
	S	21	47.6	8.1	34.0	40.0	47.0	53.0	62.0
Max Flux (m3/s)	N	44	114.0	117.7	10.0	31.5	61.5	139.3	457.0
	S	21	181.1	177.3	7.00	30.0	134.0	317.0	537.0

The probability plots of ZMAX for the 44 natural and 21 seeded clouds are shown in Fig. 7, along with the 95% confidence intervals for the corresponding normal distributions. The ZMAX values ranged from 35 to 59 dBZ in the natural clouds, and 34 to 62 dBZ in the seeded clouds. The difference between groups lies in the number of cases with high reflectivity values >50 dBZ. Half of the seeded clouds achieved greater ZMAX than the natural clouds, but the difference is not statistically significant.

The distributions of the MAX FLUX for the natural and seeded clouds are shown in Fig. 8. The MAX FLUX values ranged from 10 to 457 m^3/s in the natural clouds, and 7 to 537 m^3/s in the seeded clouds. The MAX FLUX values follow the log-normal

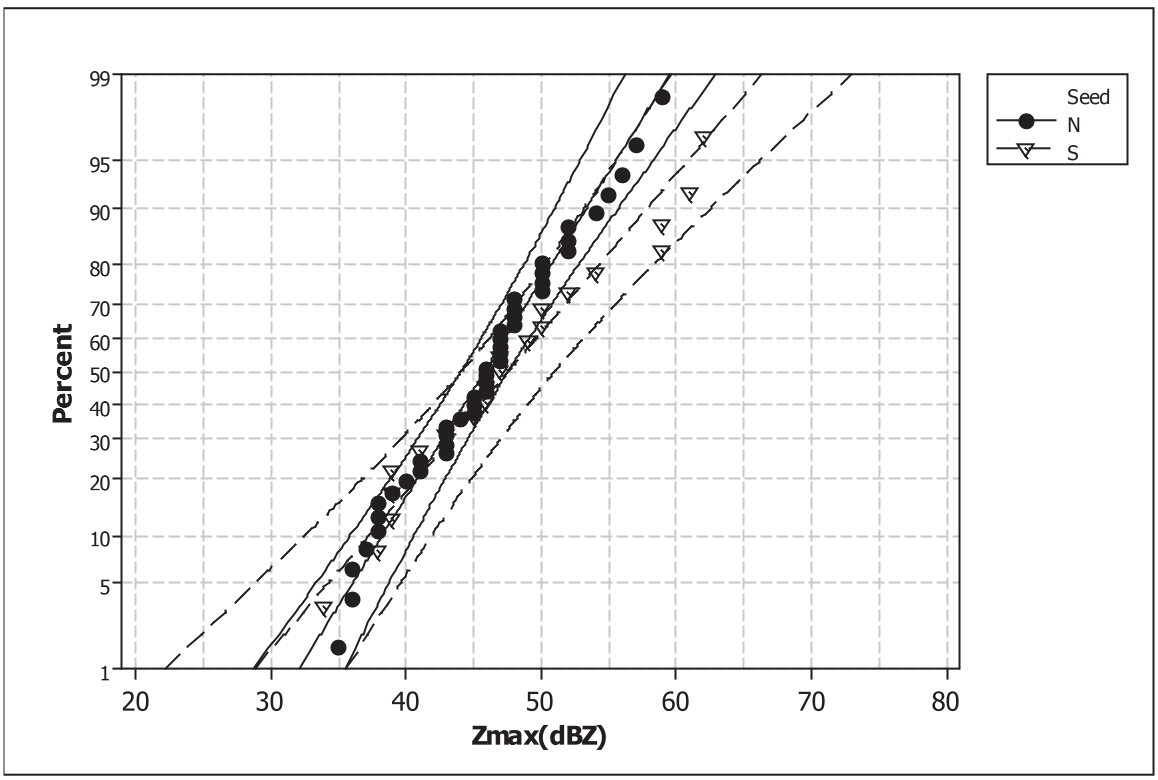

Figure 7: Probability plot of maximum radar reflectivity for 44 natural clouds (N) and 21 seeded clouds (S) that had a radar echo > 0 dBZ but < 20 dBZ at time of selection. The 95% confidence intervals for the corresponding normal distributions are also shown.

distribution as shown in Fig. 8. The median MAX FLUX equaled 61.5 m^3/s for the natural clouds, and 134 m^3/s and for seeded clouds. There is a shift in the distribution to greater values for the median, Q3, and maximum seeded MAX FLUX, compared with the natural clouds. This is another indication that seeding increases the precipitation, but the differences are once again not statistically significant. The biggest difference is indicated for clouds with maximum precipitation fluxes > 100 m^3/s. These clouds represent heavy rainfalls, consistent with the ZMAX values >50 dBZ.

7. CHARACTERISTICS OF CLOUDS SEEDED WITH RADAR REFLECTIVITY >30 DBZ AT TIME OF SEEDING

Microphysical effects of glaciogenic seeding have been shown in previous studies of simple clouds, early in their development (Cooper and Lawson 1984, Krauss et al. 1987, Sinkevich 2001). Simple clouds usually account for a small fraction of the total rainfall, and the scientific challenge is to determine the effects of seeding more mature clouds, at a later time in their life cycle. This section examines the radar characteristics of cells that were seeded after they already had radar reflectivity > 30 dBZ. The data set consists of 19 natural cells and 13 seeded cells from 8 days during August 2009.

7.1 TITAN Track Matching Results

The natural cells, used for comparison purposes with the seeded cells, were selected using the TITAN track-matching algorithms. TITAN computes the initial conditions as averages for various important parameters for the first three radar scans (15 min) of the cell lifetime. Firstly, radar cells were only chosen if they occurred between 10Z and 16Z (1300 to 1900 local time) since all seeded cells were between these times. Secondly, only cells that tracked within 150 km range of the radar were selected. Total cell mass (calculated by TITAN using the radar reflectivity, area, and height) was chosen as the primary selection parameter. Only cells that had a positive change in mass during the first 3 volume scans (i.e. growth during the first 15 min) were selected. All cells for the day were ranked according to mass, and then the natural cells that ranked immediately before and after each seeded cell were chosen for the comparison analysis.

A statistical summary of the initial Mass and Precipitation Flux for the 19 natural clouds and 13 seeded clouds are shown in Table 4. The mean, median, minimum and maximum values are all very similar; therefore, there were no significant differences or biases between the natural and seeded clouds during the first 15 min of their lifetimes.

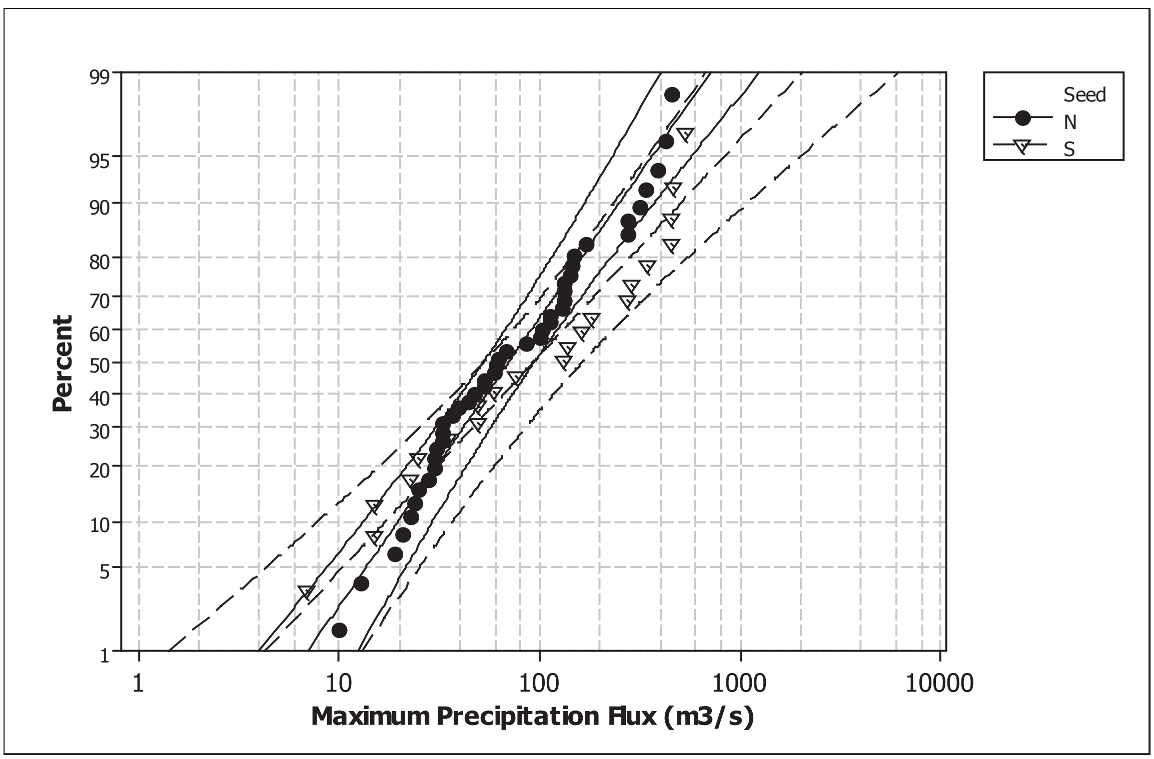

Figure 8: Probability plot of maximum precipitation flux for 44 natural clouds (N) and 21 seeded clouds (S) that had a radar echo > 0 dBZ but < 20 dBZ at time of selection. The 95% confidence intervals for the corresponding log-normal distributions are also shown.

Table 4: A statistical summary of the initial Mass and Precipitation Flux for 13 cells Seeded when their initial radar reflectivity was >30 dBZ and the corresponding matched 19 Natural cells.

Variable	SEED	N	Mean	StDev	Minimum	Q1	Median	Q3	Maximum
Mass(ktons)	N	19	23.7	20.3	3.5	5.9	19.2	37.5	75.4
	S	13	25.7	22.9	3.2	5.7	18.5	37.3	79.4
Precip_flux(m3/s)	N	19	48.8	43.8	10.5	13.9	36.7	70.9	184.8
	S	13	50.3	42.1	11.2	14.2	36.7	68.5	157.8

7.2 Radar Response Variables

Total Rain Volume (RVOL) is a parameter calculated by TITAN for the entire storm lifetime that can be used for assessment of the seeding. In fact, increasing RVOL is the ultimate goal of seeding. RVOL is computed by accumulating the rain volume from each radar scan over the lifetime of the storm. It is also the product of the Mean Precipitation Flux and the total storm Duration. The cumulative distributions of the log-transformed total Rain Volume for the 19 natural clouds and 13 clouds seeded with echo >30 dBZ are shown in Fig. 9. The RVOL values for the clouds in Group III were within the limits 1.1×10^4 to 6.2×10^7 m^3 for the natural clouds, and 6.9×10^4 to 4.2×10^7 m^3 for the seeded clouds. There is a shift in the distribution of seeded RVOL to greater values than the natural clouds.

The cause of the greater RVOL was investigated further. The relationship between cell duration and mean precipitation flux (MEAN FLUX) for the natural and seeded cells is shown in Fig. 10. For a given cell duration, seeded cells tended to have greater MEAN FLUX in most cases, and therefore, greater RVOL. Sixteen of the natural cells and 8 seeded cells lived < 1.5 hr and had MEAN FLUX values in the 10 to 200 m^3/s range. However, there were

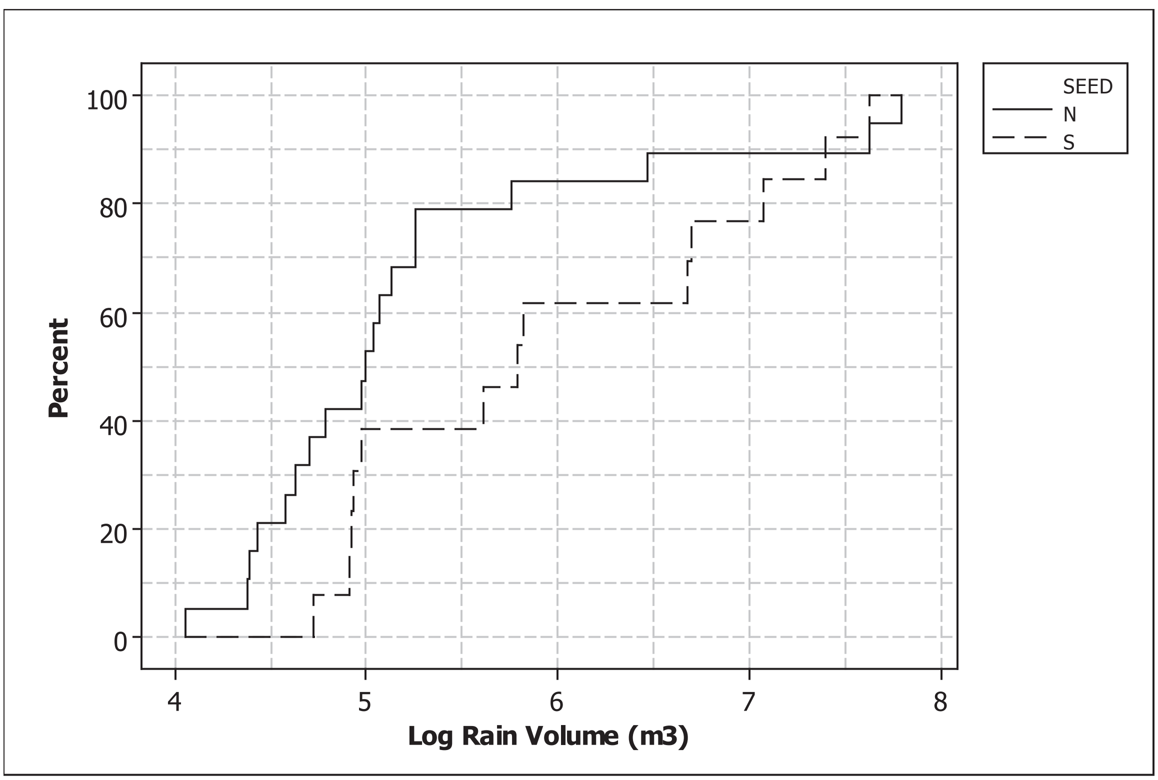

Figure 9: The empirical cumulative distributions of the log-transformed Rain Volumes for the 13 cells seeded with pre-existing echo >30 dBZ, and their corresponding, matched 19 natural cells, including the merged complexes.

5 seeded cells and only 3 natural cells that lived > 2 hr and these shifted the distribution as a whole towards greater precipitation fluxes for the seeded cases. There is a bias in the number of long-lived cells, favoring the seeded group, which cannot necessarily be attributed to the seeding.

The TITAN program keeps track of cell mergers for multi-cell storms. All of the natural and seeded storms with durations >2 hrs had multiple mergers. Storms with durations between 2 and 3 hrs had between 13 and 26 cell mergers. The seeded storm that had 3.25 hr duration had 30 mergers. The storms that had >4 hr durations had between 67 and 128 mergers, and the natural storm that lived for 6 hrs had 123 cell mergers.

Five of the seeded cells and three of the matched natural cells lived >2 hrs. Further examination of the aircraft seeding logs showed that these 5 seeded cells merged with other cells that had already existed for 40 min to 1:40 hr. TITAN then included the rain volume from the earlier cells into the resultant merged complex. After the merger, it is not possible to determine the contribution of the seeding to the resulting merged complex. The cells that were seeded and then merged, continued to live for 1 to 3 hrs after seeding, and had the greatest mean precipitation fluxes, and therefore, produced the greatest RVOL. Although the cells started out similarly (initial conditions for first 15 min were similar), some became merged complexes and others did not. Furthermore, it is not valid to attribute all of the rain from the merged-complex to the seeding. This selection bias issue is also not resolved by randomization. Further research is required into the effect of seeding feeder clouds and the effect on precipitation for the resulting convective complex.

7.3 Removal of Large Merged-Complexes

A sub-set of cells was selected for analysis by removing all cells that lived >2 hrs, and only including cells that were seeded during the first 15 min, thereby removing all the large merged complexes. The corresponding natural TITAN cell track matches were included for comparison. This reduced the sample to 18 cells (6 seeded cells and 12 natural cells) on four days (Aug, 21, 24, 26, and 31, 2009).

The cumulative distributions of the log-transformed RVOL for the reduced set of cells seeded with pre-existing echo >30 dBZ, and their corresponding matched natural cells are shown in Fig. 11.

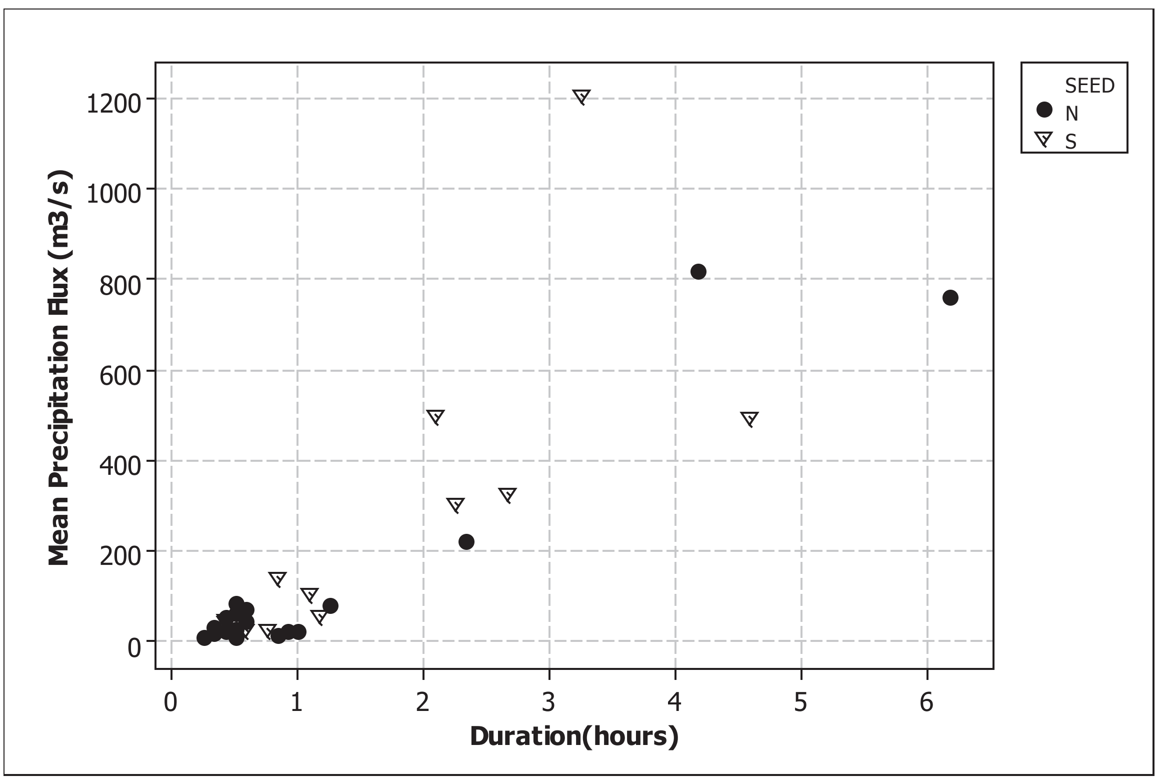

Figure 10: Scatter plot between the Cell Duration and Mean Precipitation Flux.

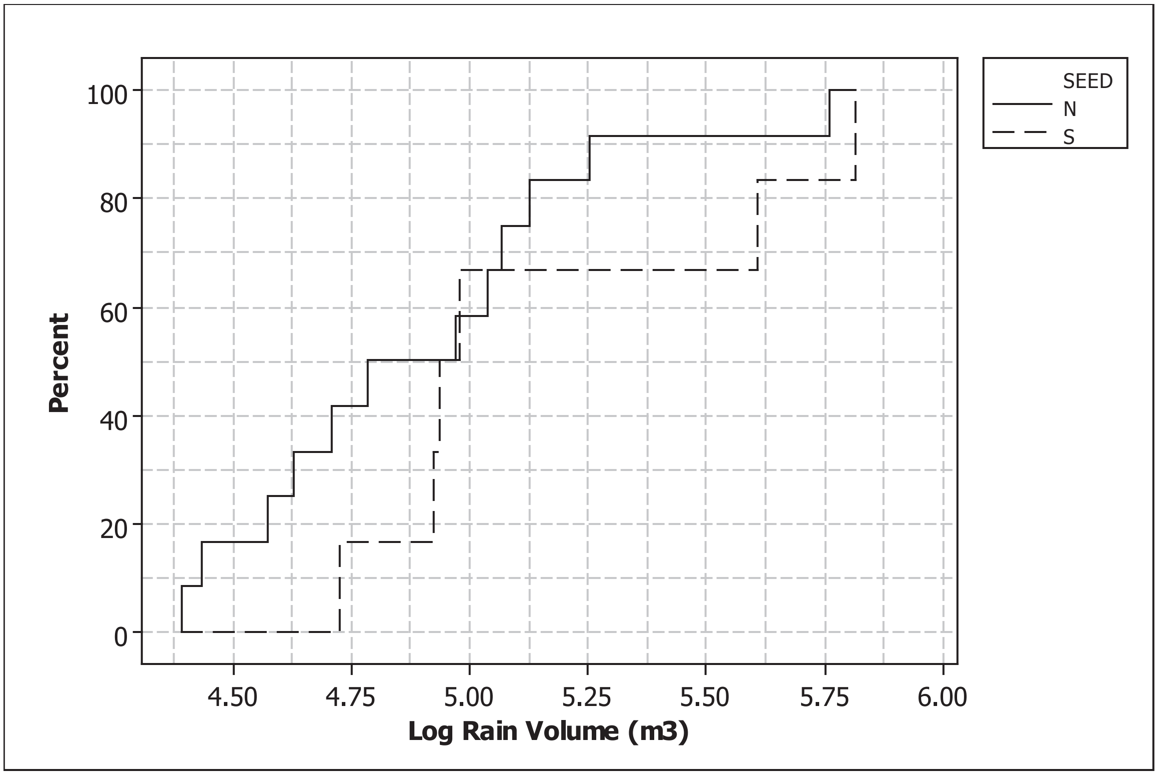

Figure 11: Cumulative distributions of the log-transformed Rain Volumes for the 6 cells seeded with pre-existing echo >30 dBZ, and their corresponding, matched 12 natural cells.

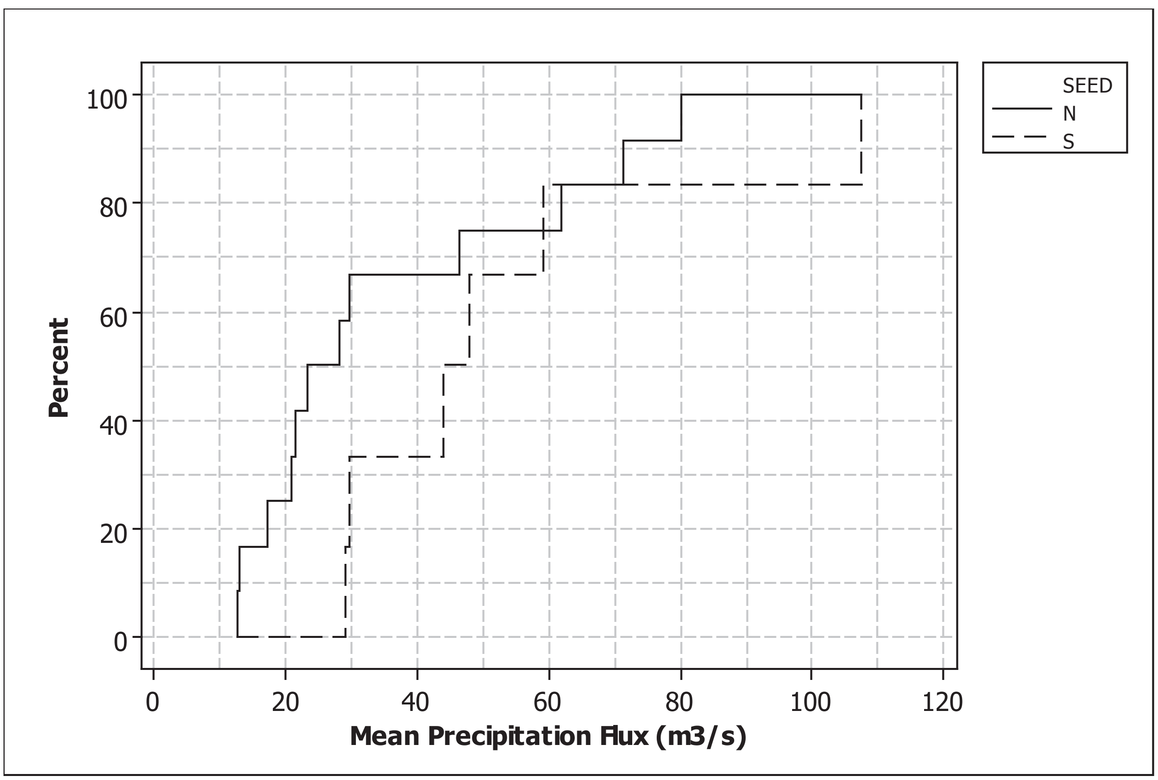

Figure 12: The empirical cumulative distributions of the Mean Precipitation Flux for the 6 cells seeded with pre-existing echo >30 dBZ, and their corresponding, matched 12 natural cells.

The cumulative distributions of MEAN FLUX for the reduced set of cells seeded with pre-existing echo >30 dBZ, and their corresponding matched natural cells are shown in Fig. 12.

There is a positive association between the seeding and greater RVOL evident in the cumulative distribution plots of Fig. 11, although the median values are similar and we must remember that the sample size is small. The positive seeding effect is a result of increased MEAN FLUX for the seeded cases as shown in Fig. 12. There were no significant differences in the storm durations and all storms had durations < 1.2 hrs. The mean ZMAX was 43.4 dBZ for the natural clouds, and 49.3 dBZ for the seeded clouds. The median values for MAX FLUX for the natural and seeded clouds were 50.2 m^3/s and 95.5 m^3/s respectively. The median values for MEAN FLUX for the natural and seeded clouds were 25.7 m^3/s and 46.0 m^3/s respectively (shown in Fig. 12). The positive association with seeding is consistent with the findings for the cells in Group I and Group II. These findings must be viewed with caution because of the small sample size, and there is need for further investigations of this type before any definite conclusions can be made.

8. DISCUSSION AND CONCLUSIONS

This study has documented the radar derived precipitation characteristics of new, developing cumulus congestus clouds both in their natural state, and those that were seeded using AgI at various stages of development, over the Asir region of southwest Saudi Arabia. These clouds represent a valuable source of water for the KSA. Radar response variables were analyzed to see if there were differences between the seeded clouds and natural clouds. Special attention was given to select similar clouds at the same time and location to those that were seeded.

Three groups of seeded clouds were studied: Group I consisted of 28 clouds seeded at a time without any radar echo, and 43 natural clouds for comparison purposes. Group II consisted of 21 clouds seeded when the radar echo was >0 dBZ but <20 dBZ, and 44 natural clouds for comparison purposes. Group III consisted of 13 clouds seeded when the initial radar echo was >30 dBZ, and 19 natural clouds for comparison purposes.

The Group I seeded clouds produced greater maximum reflectivity (ZMAX) and greater precipitation flux (MAX FLUX) than their natural counterparts. The difference in the ZMAX means was 3.3 dBZ. The median MAX FLUX for the natural clouds was 148 m^3/s and for the seeded clouds was 193 m^3/s. The differences in the mean for ZMAX and MAX FLUX were significant at the 94% and 93% level respectively. Although not significant at the 95% level, there is a very positive association between the seeding and greater ZMAX and greater MAX FLUX. The mean times to reach MAX FLUX for the natural and seeded clouds were very similar; 27.9 min and 26.1 min respectively.

The Group II seeded clouds also produced greater ZMAX and greater MAX FLUX than their natural counterparts. The difference in the mean ZMAX was 1.7 dBZ. The median MAX FLUX for the natural clouds was 61.5 m^3/s and for the seeded clouds was 134.0 m^3/s. The biggest differences between groups was for clouds with ZMAX >50 dBZ and MAX FLUX >100 m^3/s. The positive association with seeding persisted, but the statistical significance was less.

The results of the Group III clouds was dominated by a few large merged-complex storms. Five of the seeded clouds and three of the natural clouds formed large, merged complexes that dominated the radar statistics in favor of the seeded group. The seeded clouds merged with older cells and the effects of seeding could not be determined after merger. A sub-set of cells was selected for further analysis, which was seeded during the first 15 min and did not merge with older cells. This removed all of the large merged complexes and removed the bias in favor of the seeded group. Unfortunately this reduced the sample size substantially to 6 seeded cells and 12 natural cells. The positive association with seeding persisted, but the statistical significance was low, and must be considered to be very preliminary because the sample size is very small. Further research into the effects on precipitation when seeding clouds that merge with a pre-existing cell is required.

The differences between MAX FLUX for the seeded and natural clouds became less as the radar reflectivity at the time of seeding increased. The greatest seeding effects were observed for clouds that were seeded prior to the appearance of a radar echo. These statistical evaluations were not significant at the 95% confidence level; however, there is a positive association between seeded clouds and greater ZMAX, MAX FLUX and RVOL. The distributions of the response variables to seeding overlap; however, there is a consistent shift to larger values for the seeded cases. The overlap is not surprising because the responses to seeding are highly variable and fall within the range of natural variability. The authors do not believe that a blind, random selection process would necessarily account for all of the natural variability that exists. This variability is caused by seeding at slightly different times in the cloud development, with slightly different initial conditions, with slightly different seeding amounts, at slightly different locations, with slightly different topography, and slightly different forcing conditions and so on. Therefore, it is not surprising that the differences are not statistically significant at the 95% confidence level. However, this also does not mean that the differences are not positive and sufficient to warrant further assessment and considerations. The results to date have been sufficiently encouraging for the PME to continue with the cloud seeding program.

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