THE SECOND POLARIMETRIC CLOUD ANALYSIS AND SEEDING TEST

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Abstract. The Polarimetric Cloud Analysis and Seeding Test 2 (POLCAST2) program was an effort to evaluate the effectiveness of hygroscopic flares to increase precipitation in the North Dakota region. As part of the POLCAST2 program, a field project was conducted between 9 June 2008 and 11 July 2008. Thirteen randomized seeding candidates were found during twelve flights of the Cessna 340 seeding aircraft. The aircraft carried instrumentation to conduct *in situ* measurements of properties important for precipitation development, which enables seeding candidate stratification by aerosol amount. The University of North Dakota's NorthPol radar was used to continuously monitor cloud structure, measure precipitation rates, and investigate polarimetric radar observation variability between seeded and non-seeded candidates. Cloud candidates were randomly selected to be either treated with the release of hygroscopic material at cloud base by burning four sets of two flares, or instead not treated and only cloud base measurements conducted. NorthPol's radar data were ingested into the Thunderstorm Intensity Tracking Analysis and Nowcasting (TITAN) software to analyze candidate cases. TITAN analysis of six cases (an insufficient number to be statistically significant) indicated that the methodology of using polarimetric radar data to analyze "areas of influence" is promising for evaluation of possible seeding effects. Airborne measurements show that the cloud base aerosol and droplet concentrations are generally relatively high in summer time North Dakota with Passive Cavity Aerosol Spectrometer Probe (PCASP) aerosol concentration of 890 cm^{-3}, Cloud Condensation Nuclei (CCN) concentrations of 1,030 cm^{-3}, and cloud droplet concentrations of 360 cm^{-3}. The cloud base CCN concentration is higher in North Dakota than in other areas (Mali and Saudi Arabia) where similar measurements have been made. The cloud base aerosol concentration varies from day to day, and hence it is an important field to quantify when evaluating the effectiveness of hygroscopic seeding. Additional field projects are planned that will add to the number of randomized cases obtained so far, which will provide greater confidence in the POLCAST2 case study results and provide additional measurements for understanding the physical processes of precipitation development in the North Dakota region.

1. INTRODUCTION

North Dakota began using weather modification techniques in the 1950s as a cost-effective means to mitigate the economic impact to agriculture as a result of water shortages and crop loss due to hail storms. North Dakota has a long history of operational weather modification (NDCMP History, 2010) and a strong commitment to using the best available weather modification techniques, such as seeding clouds where aerosols (suspended particles) are released directly into clouds using aircraft-based deployment systems.

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To help alleviate water supply stresses, cloud seeding for precipitation enhancement has been used as a tool to mitigate dwindling water resources (Bruintjes, 1999). Operational weather modification programs are currently being conducted throughout the world even though there is limited scientific support for their underlying theoretical base and little research supporting their specific application. The American Meteorology Society's statement on Planned Weather Modification Through Cloud Seeding (American Meteorological Society, 2010) stated that cloud seeding is one tool available to mitigate the impacts of too little or too much precipitation, but recommended that research and operational programs should be designed in a way that allows for physical and statistical evaluation since the physical cause-and-effect relationship has not been fully documented. However, the potential for precipitation increases is supported by field measurements and numerical model simulations (e.g. Curic et al., 2008).

North Dakota is dedicated to using weather modification methods based on the most reliable scientific understanding. With the apparent success of the hygroscopic seeding applications in many regions of the world for precipitation enhancement (Silverman, 2003), the evaluation of hygroscopic seeding for the possible implementation in North Dakota's operational program should be conducted. It was decided that a series of research programs would be conducted to evaluate the effectiveness of hygroscopic cloud seeding. The results from these research programs will be used to determine whether hygroscopic seeding methods should be adopted by North Dakota's operational weather modification program.

Cloud seeding involves the introduction of a seeding agent such as silver iodide (AgI), dry ice, liquid carbon dioxide, or hygroscopic aerosols into a cloud. AgI seeding has been preferred in cloud modification for the past 50 years since it is an effective ice nucleus and has shown no environmentally harmful effects (WMA, 2009). Due to the lack of ice nuclei in the atmosphere, there are often areas of super-cooled liquid water in developing clouds where AgI can be introduced to convert small liquid cloud droplets into larger ice particles that will enhance the efficiency of precipitation formation. Increasing the precipitation efficiency is an effective method to increase rainfall amounts since only a small amount of atmospheric water vapor is removed during a precipitation event.

While glaciogenic seeding using an agent such as AgI is promising and worth pursuing, hygroscopic seeding has advantages over glaciogenic seeding because "warm clouds" can be seeded. The conceptual model for the hygroscopic seeding method is that releasing hygroscopic seeding material into a cloud will broaden the cloud droplet spectrum that results from condensation of water vapor onto aerosols. Furthermore, the droplet number concentration would decrease if the cloud liquid water content remains the same. While the actual process involved is still uncertain, it is thought that this broader cloud droplet spectrum will enhance the collision-coalescence process and produce more precipitation by initiating rain earlier and/or prolonging the life of a treated cloud. This conceptual model is supported by model studies (Cooper et al., 1997) that suggest that the concentration of accumulation-mode particles may influence coalescence rates by increasing the sizes of the largest drops in the initial size distribution produced by condensational growth in continental clouds (1000 cm^{-3} cloud base droplet concentration). Yin et al. (2000) found that seeding with hygroscopic flares could increase rainfall amounts in continental clouds having cloud condensation nuclei (CCN) concentrations (active at 1% supersaturation) of more than about 500 cm^{-3}, while seeding more maritime clouds resulted in reducing the integrated rain amounts. Hence, it is critical to quantify the CCN concentration when studying the effects of hygroscopic seeding.

Analysis of randomized hygroscopic cloud seeding first provided positive statistical results in South Africa (Mather et al., 1997; Silverman, 2000) and later in Mexico, Thailand, and India (Silverman, 2003). The South Africa, Mexico and Thailand analyses were based on radar derived precipitation estimates, while the India analysis used rain gauge measurements. The positive statistical results from these experiments should be taken with caution since the microphysical conceptual hypothesis cannot explain the magnitude and timing of the precipitation increases (Silverman, 2003). There are many possible mechanisms where hygroscopic seeding could increase the number of large droplets during cloud formation, while not increasing surface precipitation. Likewise, there are many possible methods where an increase in large droplets could increase precipitation. It is only by using measurements in addition to weather radar observations that the physical reason for a statistical increase in precipitation can be determined.

During the summer of 2006, the first North Dakota hygroscopic field program, Polarimetric Cloud Analysis and Seeding Test (POLCAST), was conducted to investigate if effects from hygroscopic seeding of clouds could be detected by polarimetric radar observables or by derived radar fields (Kucera et al., 2008). Differences between seeded and unseeded continental clouds are expected in radar-derived properties based on cloud microphysical models (Lin et al., 2001). Exploratory results based on eight seeded cases indicated that the polarimetric radar observations, liquid water content, rainfall rates and hydrometeor type were consistent with the hygroscopic seeding conceptual model. However, the findings were only preliminary in nature since there were far too few cases to produce any statistically significant results.

Building on the success of the first field program, a second field program (POLCAST2) was conducted during the summer of 2008. POLCAST2 was a cooperative study between the North Dakota Atmospheric Resource Board (NDARB), the University of North Dakota (UND), the National Center for Atmospheric Research (NCAR), Weather Modification Inc. (WMI), and Ice Crystal Engineering. Ice Crystal Engineering provided the flares used during the project. WMI operated the Cessna 340 aircraft (registration number N37360). The UND C-Band Polarimetric Doppler Radar (NorthPol) observed precipitation systems throughout the field project. Airborne probes were installed on the WMI aircraft to measure aerosols, CCN, and cloud droplets. The scientific objectives of the POLCAST2 field project were to:

- Better understand the effects of cloud base hygroscopic seeding of convective clouds in North Dakota.
- Determine identifiable signatures of hygroscopic seeding in polarimetric observables or derived fields.
- Characterization of the naturally occurring cloud base aerosol and CCN concentration.
- Characterization of hygroscopic seeding effects stratified by aerosol and CCN concentrations.
- Characterization of the cloud droplet size distributions.

Learning from the POLCAST field project, two major changes were made. Randomization of seeding candidates was implemented to eliminate selection bias, and airborne measurements were added to the seeding aircraft. The main objective of the airborne measurements was to allow cases to be stratified by aerosol and cloud droplet concentrations. In addition, the airborne measurements allowed for characterization of the seeding environment using *in situ* data to evaluate the physical process of precipitation formation. By collecting high quality radar and aircraft measurements, observations related to the physical processes can be related to other research projects to enable a better overall understanding of the effects of cloud seeding.

2. PROJECT DESCRIPTION

2.1 Field Operations

POLCAST2 was conducted between 9 June 2008 and 11 July 2008, with a three-day holiday break between 4-6 July (POLCAST2, 2010). This time period was chosen since it coincides with the climatological peak in rainfall for the Red River Valley area of North Dakota. Each day of operations began with a briefing that included a weather forecast, equipment operational status, and plan for the day's activities. During the daily briefings, the current day's convective forecast and outlook were discussed and a timeline was developed for that day's operations (radar operations, time of aircraft launch, location of convection, etc.). The daily briefing also served to discuss instrument issues and, if necessary, for reviewing the previous mission. Previous mission reviews included discussion of the radar and seeding aircraft operations, the seeding candidates found during the mission, and review of the airborne measurements.

On possible aircraft flight days, two UND personnel travelled from Grand Forks to Fargo (approximately 75 minute trip), where the WMI aircraft was based, to take part in aircraft flight operations. On all POLCAST2 flights, a UND flight scientist and flight engineer flew with the seeding aircraft. The flight scientist directed the airborne sampling, while the flight engineer operated the data system and ensured that all instruments were operating. The aircraft communicated with the radar operations center to target optimal seeding candidates. Only candidates located on the west side of the Red River (e.g., west of the Minnesota-North Dakota border) and within 100 km of the radar were targeted because seeding was only allowed in North Dakota and the quality of polarimetric radar degrades significantly beyond this range.

2.2 Randomized Seeding Methodology

Randomized seeding of candidates (candidate clouds) was conducted throughout POLCAST2 to enable statistical comparison of radar-derived parameters. While sufficient cases to generate statistically meaningful results could not be obtained from the short POLCAST2 program, randomized seeding was conducted with the expectation that additional field programs would be conducted, and cases obtained during POLCAST2 could be combined with future projects. A 50/50 seed to no seed ratio was used to generate a sequence of 50 decisions. A sequenced randomized number technique was employed to ensure that not too many of the same decisions occurred consecutively. The randomized decisions were placed in individually numbered envelopes and kept at the radar operations center to be opened when the seeding aircraft located a candidate.

A set of criteria were used for selecting a seeding candidate that included: the candidate was a relatively convectively isolated cloud, initial development was within 100 km of the radar, seeding was in North Dakota, the pilot estimated updraft was at least a 500 ft/min below cloud base, and cloud base temperature was between 4 °C and 20 °C. After the aircraft crew identified a candidate that met the seeding criteria, a "Seed" or "No Seed" decision was requested by radio from the radar operations center. The radar operator would open an envelope and report the decision to the aircraft crew. The aircraft crew would then fly in the updraft region under cloud based, burning flares for a "Seed" decision and not burning flares for a "No Seed" decision. Flying under cloud base after a "No Seed" decision allowed the aircraft flight track to clearly mark the cloud candidate area and allow for measurements of aerosols below cloud base.

The Cessna 340 aircraft was equipped to carry twelve hygroscopic flares on each aircraft wing (Figure 1). Two flares, one flare on each wing, would be lit at one time. Treatment of a cloud candidate consisted of four sets of flares and took a total of approximately twelve minutes. Potassium chloride was the nucleating material released by the Ice Crystal Engineering LLC hygroscopic flares used during POLCAST2. Flare particles with a mean diameter of 1 μm and geometric standard deviation of 0.4 μm were primarily responsible for the enhanced rate of precipitation formation (Cooper et al., 1997). The large diameter hygroscopic particles generated by burning flares will activate preferentially over smaller sized naturally occurring particles.

2.3 Radar Measurements

During POLCAST2, the NorthPol radar was used to make continuous measurements. Basic radar specifications are given in Table 1 with more information available on the NorthPol's web site (NorthPol Radar, 2010). The NorthPol radar was operated in full-volume Plan Position Indicator (PPI) or sector scan mode. NorthPol collected a variety of radar observables, which included radar reflectivity, doppler velocity, differential reflectivity, differential phase, specific differential phase, and the correlation between the horizontal and vertical polarimetric fields (see Bringi and Chandrasekar [2001] and references therein for complete descriptions of polarimetric parameters). A radar calibration performed before the start of POLCAST2 indicated no significant difference from the previous calibration.

Figure 1: Images showing the research instruments and hygroscopic seeding rack on the Cessna 340 aircraft.

Table 1: List giving the parameters of the NorthPol radar. The NorthPol radar is located on the west side of the University of North Dakota's campus on top of Clifford Hall at latitude 47.92190 degrees and longitude -97.08664 degrees.

Radar Parameter	Value
Peak Output Power (kW)	250
Wavelength (cm)	5.4
Pulse Width (microsecond)	0.6, 2.0
Antenna Gain (dB)	43.75
Elevation Range (°)	-0.5 – 90
Antenna Height Above Ground (m)	28
Beam Width (degree)	0.99
Minimum Detectable Signal (dBm)	-114
Maximum Scan Speed (°/sec)	20
PRF (Hz)	250-1200
Polarization	Linear Horizontal and Vertical
Variables	ZH, VR, s, ZDR, KDP, ΦDP, ρHV
Data System	SIGMET IRIS

2.4 Airborne Measurements

During POLCAST2, the seeding aircraft was equipped with a limited set of instrumentation that included:

- Particle Measuring Systems (PMS) Forward Scattering Spectrometer Probe (FSSP – Serial Number 277-0676-06) (Able to measure cloud droplets between approximately 3 and 47 μm diameter.)
- PMS Passive Cavity Aerosol Spectrometer Probe (PCASP – Serial Number 30013-1191-11) (Able to measure particles between approximately 0.1 and 3.0 μm diameter.)
- Droplet Measurement Technologies (DMT) Hot Wire Liquid Water Probe (LWP- Serial Number 36278) (Able to measure cloud liquid water content.)
- University of Wyoming Cloud Condensation Nuclei Counter (CCNC – Serial Number 107) (Able to measure the concentration of aerosols that activate at supersaturation between 0.3 and 1.6 %.)
- EdgeTech Digital Aircraft Hygrometer (Serial Number 36278) (Able to measure dew point temperature.)
- Rosemount Aircraft Temperature Sensor (Serial Number 52533) (Able to measure total temperature.)
- Global Positioning System (GPS) (Able to measure position and ground speed.)
- Pressure transducers (Able to measure static and dynamic pressure.)
- Science Engineering Associates (SEA) M300 data system (Serial Number 3038) (Able to acquire and record data from all aircraft instruments.)
- Hygroscopic cloud seeding racks (Able to carry up to 24 flares).

Figure 1 illustrates the cloud, aerosol, and meteorological instrumentation deployed on the seeding aircraft. The instrument's measurements were all recorded using the SEA M300 data acquisition system. The seeding aircraft was equipped with two PMS cans that housed an FSSP and a PCASP. The FSSP was used to measure cloud droplet spectra within a few km of cloud base and the PCASP was used to measure the aerosol size spectra below cloud base.

3. PROJECT SUMMARY

3.1 Aircraft Flights

A total of 12 flights (24.83 hours) were conducted between 10 June and 11 July 2008 as part of POLCAST2 (Table 2). Figure 2 shows the flight tracks for all flights where research measurements were obtained. An area where there is a race-track (oval shape) flight pattern indicates a possible seeding candidate. Cases where there are several laps around the race-track indicates a seeding candidate, while having only one lap means that the area was investigated but conditions were not suitable for a seeding candidate. A total of thirteen randomized potential hygroscopic seeding candidates were found, of which seven were actually seeded.

Table 2: Summary of aircraft flights conducted during the POLCAST2 field project. The June 10 flight was for instrument testing while all other flights were research flights.

Start Date	Start Time	End Time	Total Time	Cloud Base Height	Cloud Base Temperature
yymmdd	hh:mm:ss	hh:mm:ss	Hours	Meter	Degrees Celcius
080610	22:46:47	23:27:30	0.68	1150	4
060612	19:24:43	20:33:37	1.15	1750	4
080612	21:52:43	23:55:21	2.04	2100	3
080613	18:19:08	21:32:41	3.23	1600	6
080614	20:24:45	22:32:19	1.58	2400	4
080619	21:19:54	22:42:50	1.38	2100	8
080621	20:57:32	22:53:01	1.95	2200	4
080626	21:57:00	00:24:42	3.46	2250	9
080701	22:41:52	01:02:48	2.39	1650	10
080707	22:45:17	00:55:28	3.17	1400	9
080709	19:41:54	21:25:18	1.74	2200	7
080711	19:10:58	21:15:20	2.07	950	22

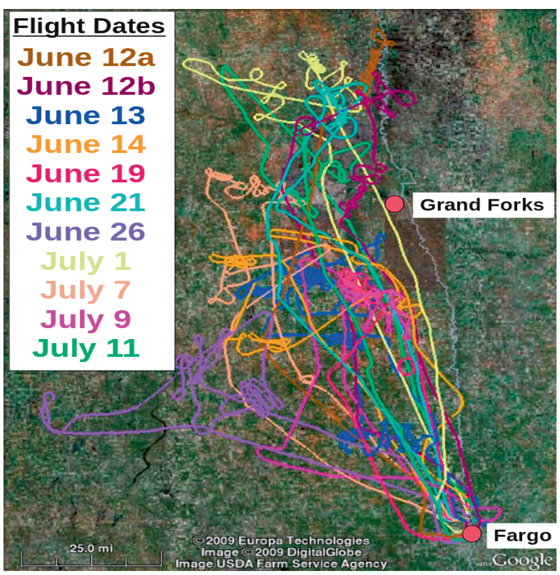

Figure 2: Flight tracks for seeding aircraft flights conducted during POLCAST2. The aircraft was based out of Fargo, North Dakota and the NorthPol radar was located in Grand Forks, North Dakota. The white line between Fargo and Grand Forks is the Red River of the North and is the boundary between North Dakota and Minnesota.

3.2 Airborne Instrument Performance

Due to the pre-project calibration and the integrations testing of the aircraft instruments at the University of North Dakota, the installation of the aircraft instruments went very well. Having sufficient time to get instruments lined up, calibrated, and software working is very important to successful field measurements. The Aircraft Data Processing and Analysis open source software package (Delene, 2011) was used to process and analyze the POLCAST2 airborne measurements. Data processing was done by starting with the raw M300 data system files and processing them to automatically generate (or regenerate) derived parameters using bash and csh scripts. The data processing was done using the concept of data levels whereby data at higher data levels is derived from the next lowest data level. The concept of missing value codes was fully incorporated within the dataset. A standard ASCII data file was used for all data files except the low level raw M300 data. All ASCII data files include a header containing meta-data that fully describes the parameters contained within the file. In addition to all the airborne measurements, the dataset also includes all auxiliary data such as flight notes, field problem descriptions, analysis plots, and dataset meta-data. The dataset meta-data includes a directory structure description, a description of the mega-data header contained in each ASCII data file, and a list of the exact instruments used during the measurement program.

Cloud Condensation Nuclei Counter

During the POLCAST2 project, a University of Wyoming Cloud Condensation Nuclei (CCN) counter (Delene and Deshler, 2000) was used to make airborne measurements of cloud condensation nuclei concentrations. The CCN counter was calibrated by the University of Wyoming in May 2008 before the start of the POLCAST2 project and applied to all project measurements. The concentration uncertainty is approximately 10% at a 1% supersaturation (Delene and Deshler, 2000). The CCN counter's supersaturation reported here is based on the measured plate temperatures and a chamber model. This supersaturation is approximately 40% larger than the supersaturation derived from monodispersed test particles and a Köhler model (Snider et al., 2006); however, it is consistent with the supersaturation values quoted previously in literature for University of Wyoming CCN counter. A simple rear facing, unheated inlet located at a forward window was used to sample CCN concentration. The CCN counter was run at an instrument calculated constant supersaturation of 1% with some ground supersaturation spectra taken during the project.

During the 21 June 2008 flight, the CCN counter system had a leak that resulted in unusable data for the whole flight. The 21 June leak was not present on previous flights and points to the importance of an experienced scientist reviewing instrument measurements throughout a field project. The onboard flight scientist noted the low but believable CCN counter concentration during the 21 June flight, a post flight review of the CCN counter's raw photodetector voltage indicated a leak, and follow-up pressure testing with a handheld vacuum pump confirmed the leak. The leak was fixed on 23 June 2008 and all later POLCAST2 flights had valid CCN measurements.

Passive Cavity Aerosol Spectrometer Probe

During the POLCAST2 project, a Passive Cavity Aerosol Spectrometer Probe (PCASP) was used to make aerosol spectrum measurements. The PCASP was calibrated by DMT on 16 May 2008 before the start of the field project. The 16 May 2008 222 nm bead calibration was used to set the size channels for the POLCAST2 field project. As illustrated in Table 3, the calibration was consistent throughout the project since all performance checks using 222 nm beads had an average channel difference of less than 0.16 from the calibrated value of 5.16. The average channel values (Avg) is calculated using the equation:

$$Avg = \frac{CH_1*Cnt_1+CH_2*Cnt_2+CH_3*Cnt_3}{Cnt_1+Cnt_2+Cnt_3} \qquad \text{Eq. 1}$$

where CH is the channel number and Cnt is the number of particles counted in the channel within the time duration when calibrated beads passed though the instrument. The subscript 1 is for the pre-peak channel, the subscript 2 is for the peak channel, and the subscript 3 is for the post-peak channel.

Forward Scattering Spectrometer Probe

During the POLCAST2 project, a Forward Scattering Spectrometer Probe (FSSP) was used to make airborne cloud droplet concentration measurements. The FSSP used had the DMT SPP-100 electronic modification, which enabled measurements in twenty size channels (from approximately 3 to 47 μm) at a frequency of 10 Hz. Additionally, the new electronic does not have significant dead-time like the older FSSP electronics. Figure 3 shows the average channel values obtained on two days before the start of the project and one day after the end of the project. Borosilicate Glass Microspheres from Thermo Scientific (Thermo Scientific, 2010) of known sizes were used for all FSSP performance checks. The average channel values (Eq. 1) are approximately one channel low when compared to the theoretical average channel value. The 9 June 2010 performance check was used to calibrate the instrument and applied to all POLCAST2 FSSP measurements. Figure 4 illustrates the difference between using the standard size boundaries for the FSSP and the calibrated values. The difference in channel boundaries resulted in the calculated liquid water content (LWC) changing from 0.52 to 0.77 g/m^3.

Hot Wire Liquid Water Probe

During POLCAST2, a DMT Hot Wire Liquid Water Probe (LWP) was used to make airborne cloud liquid water content measurements. The DMT LWP is a hot wire type probe similar to that described by King et al. (1978). The probe operates by exposing a heated wire to the free air stream and maintaining the wire temperature at 125 °C. A temperature sensing "bridge" circuit detects the resistance changes in the sensing wire as temperature changes. As the resistance of the wire goes down when the wire is cooled, the power is increased to maintain a constant tem-

Table 3: Summary of performance checks conducted on the Passive Cavity Aerosol Spectrometer Probe (PCASP). The 16 May 2008 values were determined from the Droplet Measurement Technology (DMT) calibration report for which some of the parameters listed were not available (NA). POLCAST2 used the 222 nm beads (bold fonts) to calibrate the size channels of the PCASP. The Date column lists the date that the performance check was conducted. The Start and End column lists time interval in seconds from midnight (sfm) for which calibration beads were passing through the PCASP. The Peak Ch column lists the channel with the most particle counts. The Pre-Peak, Peak, and Post-Peak columns list the average number of particles in the channel before the peak counts, at the peak counts, and after the peak counts, respectively. The Size column lists the size of the beads used. The Bead Expiry Data is bead container expiration date. The Average Channel column lists the calculated average channel values based on the pre-peak, peak and post-peak counts.

Date [yy/mm/dd]	Start [sfm]	End [sfm]	Peak Ch	Pre Peak Counts	Peak Counts	Post-Peak Counts	Size [nm]	Bead Expiry Date	Average Channel
08/05/16	NA	NA	14	200.0	1,000.0	0.0	1,992	NA	13.83
08/05/16	NA	NA	8	170.6	615.6	100.5	430	NA	7.92
08/05/16	NA	NA	11	247.1	970.6	47.1	930	NA	10.84
08/05/16	**NA**	**NA**	**5**	**110.3**	**1358.6**	**409.0**	**222**	**NA**	**5.16**
08/05/28	**16,555**	**16,800**	**5**	**43.05**	**997.1**	**368.5**	**222**	**OCT 2010**	**5.23**
08/05/28	17,100	17,340	6	2.1	735.2	436.4	300	DEC 2010	6.37
08/05/28	17,640	17,880	14	10.7	41.4	10.9	2,000	DEC 2010	14.00
08/05/29	**12,200**	**12,800**	**5**	**40.1**	**939.1**	**380.4**	**222**	**OCT 2010**	**5.25**
08/05/30	**16,540**	**16,900**	**5**	**43.4**	**1,007.2**	**375.2**	**222**	**OCT 2010**	**5.23**
08/05/30	17,040	17,425	6	2.2	732.5	435.0	300	DEC 2010	6.37
08/05/30	**18,120**	**18,520**	**5**	**5.9**	**123.8**	**57.6**	**222**	**OCT 2010**	**5.28**
08/05/30	18,520	18,820	6	0.9	137.5	134.8	300	DEC 2010	6.50
08/06/09	**72,900**	**73,100**	**5**	**106.3**	**3,037.1**	**1,613.8**	**222**	**OCT 2010**	**5.32**
08/06/09	73,350	74,050	6	2.7	244.7	166.5	300	DEC 2010	6.40
08/06/17	**75,350**	**75,593**	**5**	**34.8**	**647.3**	**322.4**	**222**	**OCT 2010**	**5.29**
08/06/17	75,783	76,039	6	3.0	382.0	218.8	300	DEC 2010	6.36
08/06/25	75,260	75,690	2	328.8	840.0	442.0	140	NA	2.07
08/06/26	**76,170**	**76,500**	**5**	**146.5**	**1203.8**	**525.9**	**222**	**OCT 2010**	**5.20**
08/06/26	76,800	77,040	6	17.5	1157.3	642.9	300	DEC 2010	6.34

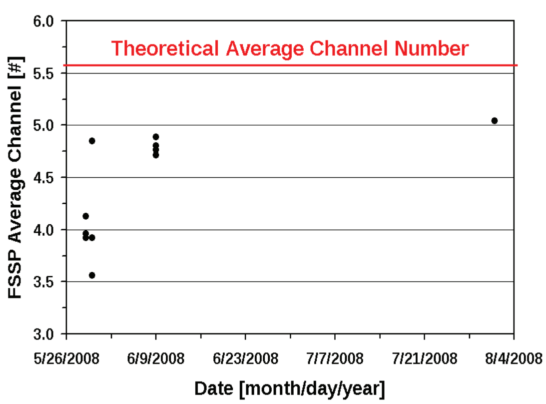

Figure 3: Average channel values for the Forward Scattering Spectrometer Probe (FSSP - Serial Number 277-0676-06) used during POLCAST2 when sampling 15 µm particles. The red horizontal line denotes the theoretical values based on an idealized optical system.

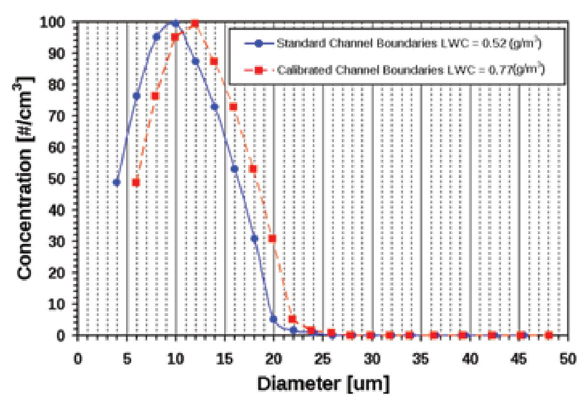

Figure 4: Cloud droplet spectra obtained on 11 July 2008 at 71,367 seconds from midnight using the standard channel boundaries (blue) and the calibrated channel boundaries. The liquid water content (LWC) given for each spectrum is given in the text box.

perature. When the probe flies in a cloud free atmosphere, the wire is mainly cooled by advection, which is proportional to airspeed and air density. When the probe flies in clouds, in addition to heat removal due to advection, liquid water impacts the wire and is vaporized which removes heat from the wire due to the energy necessary to evaporate the water. As energy is removed, the resistance changes, and additional power is applied to the wire to maintain a constant temperature. This increase in power over that required for dry air temperature is thus proportional to the cloud liquid water content (M) and is given by the equation (King et al., 1981):

$$M = \frac{P_T - C(T_w - T_a)\rho v^x + a}{ldv[L_v + C_w(T_v - T_a)]} \quad \text{Eq. 2}$$

where P_T is the total wire power, C, X, and a are calibration constants, ρ is density, *v* is true air speed, T_w is the wire temperature (125˚C for DMT LWC probe), T_a is the air temperature in degrees C, T_v is the temperature of the drops as they vaporize (90˚C for the DMT hotwire probe), l and d are the length and diameter of the sensing coil, L_v is the latent heat of vaporization and C_w is the specific heat of water.

Calibration of the LWP requires determining the constants C, X, and a. Using an empirical calibration method that fits aircraft data does not require computing the conductivity of the air through the use of Nusselt and Reynolds numbers. As first suggested to us by DMT engineers, an empirical calibration procedure that uses density should be independent of altitude. The following equation is used to determine the power (P_d) required to maintain a constant temperature in a cloud free (dry) atmosphere.

$$P_d = C(T_w - T_a)(v\rho)^x + a \quad \text{Eq. 3}$$

Figure 5 shows the data fit for the 9 July 2008 flight where LWP calibration constants were determined. The fit between measured voltage and true air speed multiplied by density shows two different sets of data points. Hence this linear fit equation does not provide a very accurate dry term calibration. Therefore, in addition to this calibration, a compensating baseline algorithm was used to adjust the baseline dry power (P_d) for each cloud penetration. When not in the cloud, the baseline correction algorithm artificially adjusts the liquid water content to have a zero value. A drawback to this method is the need to determine cloud free time periods using an FSSP.

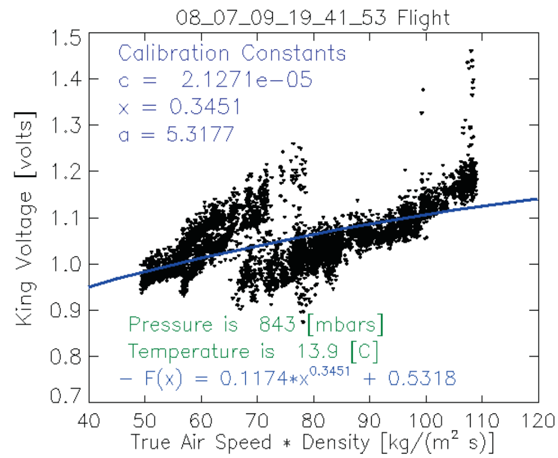

Figure 5: Calibration fit using data from the 9 July 2008 (time period of 76,300 – 76,550 [sfm]) POLCAST2 aircraft flight. Blue line indicates fitted curve with the equation given at the bottom in blue text. The calibration constants for Eq. 3 are given in the top blue text.

4. AIRCRAFT MEASUREMENTS ANALYSIS

During POLCAST2 there were eleven flights that obtained valid airborne measurements (Figure 2). Analysis of all POLCAST2 airborne data shows that CCN concentrations (1% supersaturation) are generally larger than the PCASP aerosol concentrations (Figure 6). Increasing CCN concentrations correspond to larger PCASP concentrations; however, for a given PCASP concentration (e.g. 1500 cm^{-3}), there is a large range of CCN values (~500 to 3000 cm^{-3}). This range of CCN concentrations is due to instrumental errors, differences in sampling location and frequency, and differences in aerosol chemistry and size distribution. At a lower supersaturation (e.g. 0.5%), the CCN concentration would of course decrease and there would be fewer measurements where the CCN concentration exceeds the PCASP concentration. However even for hydrophilic particles, there is no reason to expect one-to-one agreement between CCN and PASP concentration since particles below the PCASP size threshold (~100 nm) can still activate to form CCN at 1% supersaturation.

The cloud base aerosol concentrations for summertime convective clouds in North Dakota are high compared to winter time (2008) measurements in Central (near Riyadh) Saudi Arabia and summertime rainy season measurements in Mali (near Bamako), West Africa (Figure 7). The aerosol type in each of these regions was continental with no major sea salt component; however, Saudi Arabia has a major dust component, while Mali experiences some dust events. Most days sampled during POLCAST2 had CCN concentrations above

500 cm^{-3} (Figure 6). Modelling studies (e.g. Yin et al., 2000) conclude that the rainfall amount can be increased using hygroscopic flares at these CCN concentrations. Hence, based on these studies and our conceptual model, the relatively high aerosol concentrations in North Dakota indicate that hygroscopic seeding has a great potential to increase the efficiency of precipitation formation.

The POLCAST2 (North Dakota, 2008) mean cloud base temperature and altitude (GPS) were 7.3 °C and 2000 m, respectively. In Mali, the mean cloud base air temperature and altitude were 22.3 °C and 1600 m, respectively. In Central Saudi Arabia (Winter, 2008), the mean cloud base air temperature and altitude were 7.3°C and 3700 m, respectively. These cloud base values indicated that in each location clouds form in very different environments which may affect the effectiveness of hygroscopic cloud seeding. Hence, it is important to conduct airborne measurements when trying to evaluate the effectiveness of cloud seeding.

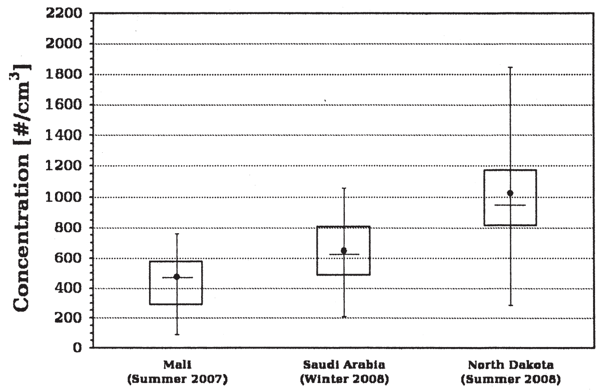

Figure 7: Statistical distribution below (100-400 m) cloud base from all aircraft flights with valid Passive Cavity Aerosol Spectrometer Probe (PCASP) concentrations. The solid circle is the mean value, the horizontal line is the 50th percentile, the top of the box is the 75th percentile, the bottom is the 25th percentile, and the top and bottom of the whiskers are the 95th and 5th percentiles, respectively. The mean concentration was 474 cm^{-3} in Mali (Bamako Area), 648 cm^{-3} in Saudi Arabia (Riyadh Area), and 1023 cm^{-3} in North Dakota. Measurements are from 9 samples in Mali (7 August to 18 September 2007), 14 samples in Saudi Arabia (14 December 2007 to 28 March 2008), and 12 samples in North Dakota (12 June to 11 July 2008).

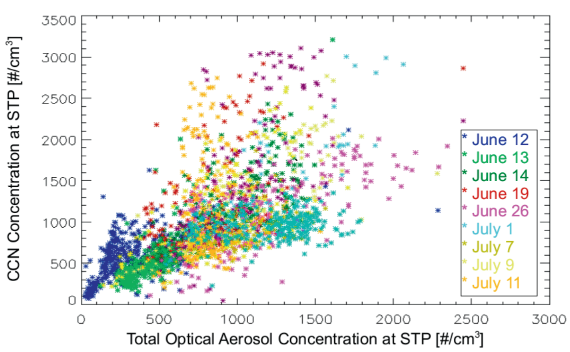

Figure 6: The 1 Hz averaged 0.1 – 3.0 µm in diameter aerosol concentration measured by the Passive Cavity Aerosol Spectrometer Probe (PCASP) at the time corresponding to samples made by the Cloud Condensation Nuclei (CCN) counter. All valid out of cloud measurements (FSSP number concentration less than 50 cm^{-3}) obtained during the POLCAST2 field project are presented. The CCN counter's supersaturation was set to 1%. Both the PCASP and CCN counter concentrations have been adjusted to standard temperature and pressure.

The cloud base aerosol and droplet concentrations vary from day to day as shown in Figure 8. The four flights from Jun 14 – Jul 1 have higher aerosol concentrations compared to the two flights before and the two flights after this period. These differences are important when evaluating the effectiveness of hygroscopic seeding (Yin et al., 2000). The mean CCN concentration of greater than 1000 cm^{-3} on the Jun 14 – Jul 1 flights is larger than any of the lower troposphere mean CCN concentration (1% supersaturation) obtained by the University of Wyoming balloon-borne CCN counter during flights above Laramie, Wyoming (Delene and Deshler, 2001). However, having CCN concentrations above 500 cm^{-3} 80% to 90% of the time (Figure 8) is consistent with surface-based measurements made in Western North Dakota on summer convective weather days (Detwiler et al., 2009).

Figure 8 illustrates that airborne measurements allow for seeding cases to be stratified into high and low aerosol concentration days. The lower right panel of Figure 8 shows that as the number of cloud base CCN increase, the number of cloud droplets increase. The coefficient of determination (R^2) is 0.37 while the correlation coefficient is 0.61. This correlation does not take into account difference in supersaturation experienced by the cloud parcel; furthermore, cloud based aerosol measurements were at a different time than in cloud measurements. The aircraft would first sample properties below cloud base and then ascend to 500-1000 ft above cloud base to make cloud micro-physical measurements. The day-to-day differences shown in Figure 8 are likely due to different air mass source regions and well-mixed lower tropospheric layer depths.

Figure 9 gives the cloud droplet concentration measured by the FSSP during POLCAST2. Only near cloud base droplet concentrations were sampled during POLCAST2. Like the aerosol concentration (Figure 6 and Figure 8), the cloud droplet concentrations are high with approximately 5% of the measurements over 550 cm^{-3}. The average median cloud base droplet concentration during POLCAST2 was 360 cm^{-3} (average median in the lower right panel of Figure 8). This corresponds to an average median cloud base CCN concentration of 1,030 cm^{-3} and an average median PCASP aerosol concentration of 890 cm^{-3}. The bottom plot of Figure 9 shows that as the FSSP mean diameter increases, the liquid water content increases; however the relationship is different on different days (e.g. June 26 and July 9).

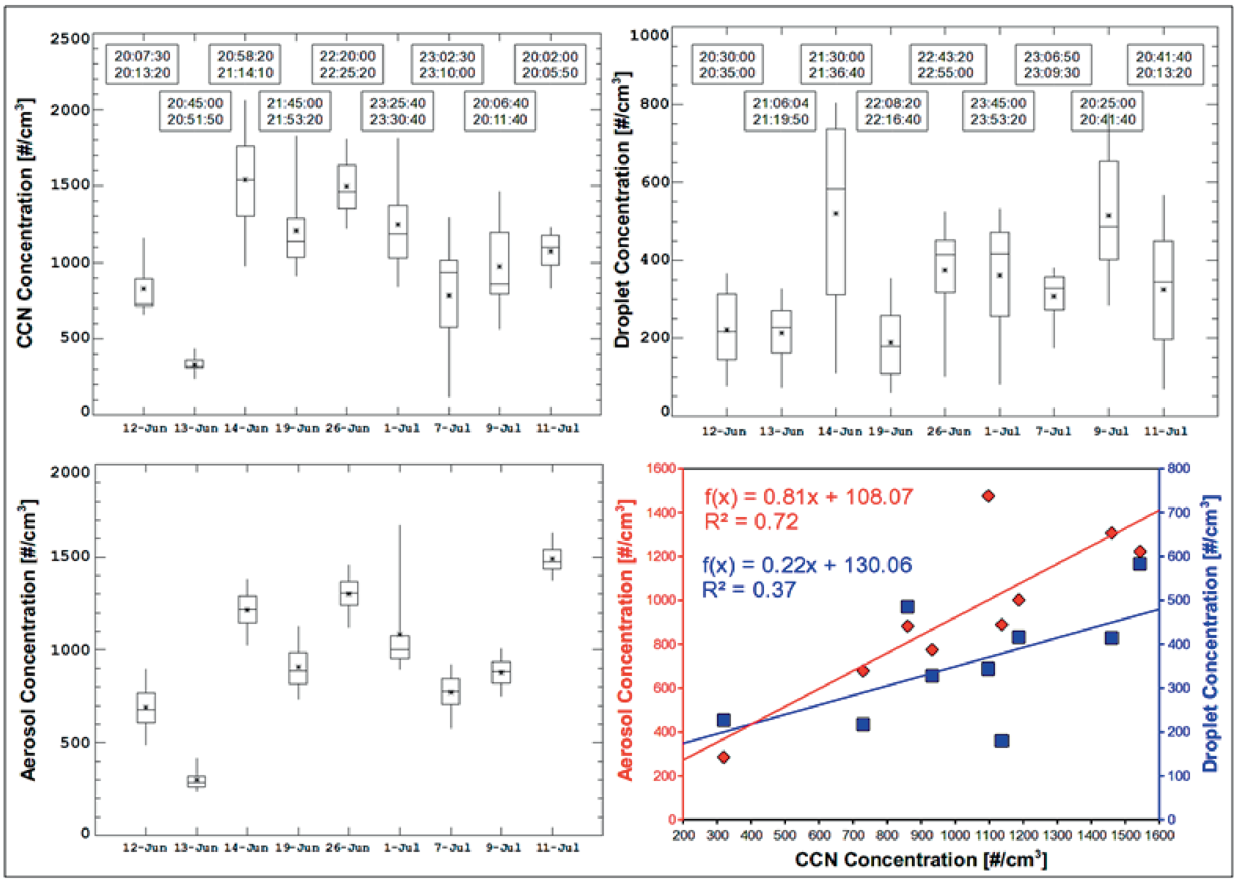

Figure 8: *Statistical distributions near cloud base of the 30 s Cloud Condensation Nuclei (CCN), 1 Hz cloud droplet and 1 Hz Passive Cavity Aerosol Spectrometer Probe (PCASP) aerosol measurements for flights during the 2008 POLCAST2 field project. All concentrations are adjusted to standard temperature and pressure conditions. The solid circle is the mean value, the horizontal line is the 50th percentile, the top of the box is the 75th percentile, the bottom is the 25th percentile, and the top and bottom of the whiskers are the 95th and 5th percentiles, respectively. The boxes in the top left panel give time intervals for the CCN and total aerosol measurements. The boxes in the top right panel give the time intervals for the cloud droplet measurements. The lower right panel compares the median (50th percentile) cloud base CCN concentration with the median aerosol concentration (red) and with the median cloud droplet concentration (blue) for the dates given in the other three panels. The least squares linear fit equations and coefficient of determination (R^2) are given in the color-coded text in the upper left of the lower right panel.*

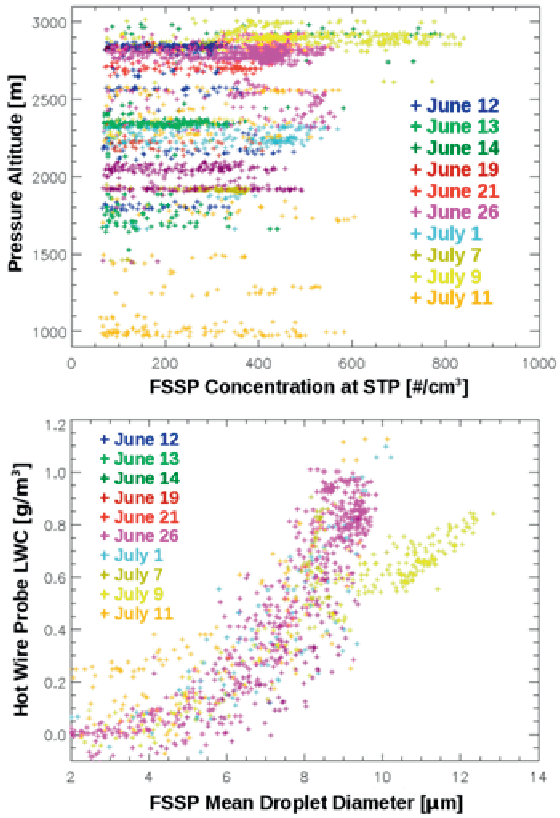

Figure 9: The top plot presents the 1 Hz Forward Scattering Spectrometer Probe (FSSP) cloud droplet concentration at standard temperature and pressure versus pressure altitude for all POLCAST2 flights. The bottom plot presents the FSSP mean droplet diameter versus the Hot Wire Probe Liquid Water Content (LWC). Only measurements with concentrations (adjusted to standard temperature and pressure) above 50 cm^{-3} are presented.

5. RADAR MEASUREMENTS ANALYSIS

The NorthPol radar data was converted from the IRIS data format to the Thunderstorm Identification Tracking Analysis and Nowcasting (TITAN) data format (Dixon and Weiner, 1993). This enabled two TITAN scripts, AcTrack2Polygon and AdvectPolygon, to be used in the data analysis. AcTrack2Polygon takes aircraft flight tracks and creates a polygon around the fight track given a specified time interval. Polygons created from flight tracks were used to mark "area of influence" for both seeded (when flares were burning) and unseeded cases. AdvectPolygon takes the polygon created by AcTrack2Polygon and advects the analysis area using the horizontal components of the TITAN track vector. The flight tracks created during hygroscopic seeding form a racetrack pattern (oval shape) that is repeated several times while seeding or sampling a candidate cloud. Hence, everything within the "area of influence" polygon is treated to some extent with hygroscopic aerosols.

The average rain rate and differential reflectivity (Z_{DR} = 10 log(Z_h/Z_v) where Z_h is horizontally-polarized reflectivity and Z_v is vertically-polarized reflectivity) were calculated within each polygon. Z_{DR} is a reflectivity-weighted parameter that is sensitive to the shape of hydrometeors. Drops with diameters greater than approximately 1 mm (Pruppacher and Pitter, 1971) tend to fall with an oblate orientation (like a hamburger bun); hence, a field of drops will have a larger cross-section in the horizontal compared to the vertical. Therefore, Z_{DR} of a field of drops as a whole indicates if large drops are present.

Marshall-Palmer rain rate calculation was changed to the National Weather Service's WSR-88D Deep Summer Convection algorithm where the rain rate (R) in mm h^{-1} is given by the following equation.

$$R = \frac{z^{1.4}}{300} \qquad \text{Eq. 4}$$

z is reflectivity in linear units of mm^6 m^{-3}.

POLCAST2 was able to collect data on thirteen randomized potential seeding candidates, with seven candidates being seed cases and six candidates being no-seed cases (Table 4). Although the NorthPol radar operated successfully during all aircraft flights, only six of the thirteen candidates developed sufficiently to produce returns within the "area of influence" to be analyzed. Based on the conceptual model of how hygroscopic seeding works, seeding needs to be performed on candidates before they develop radar echoes; hence, not all candidates develop clouds that have droplets of sufficient number and size to be detectable by the NorthPol radar. Therefore, while there were thirteen potential seed candidates, there were only six cases analyzed, three seed and three no seed.

Figure 10 shows that four out of six cases had their maximum differential reflectivity at time zero after seeding or sampling stopped, and a steady decrease with time. This is not unexpected since modeling results (Yin et al., 2000) indicate these types of clouds have maximum reflectivity 10-20 minutes after formation. Hence, large drops are predicted to form quickly and early in the cloud's life cycle and then decrease; therefore, differential reflectivity would likewise start high and then decrease. It is also not unexpected that the duration of some cloud candidates (13 June cases) does not last for 50 minutes after the completion of seeding or sampling. Time zero is approximately 12 minutes after

Table 4: List of the thirteen candidates obtained during POLCAST2 field project. The Decision column lists if the candidate was seeded or not. The Time column gives the time period of the flight track interval used to determine the "area of influence" polygons. The Analyzed column lists if sufficient radar echoes were produced within the "area of influence" to allow data analysis to be performed. The letters in parentheses are labels for referencing the two 26 June 'No Seed' analyzed cases.

Date	Decision	Time (UTC)	Analyzed
13 June 2008	Seed	18:49 – 19:00	Yes
13 June 2008	No Seed	19:12 – 19:25	Yes
13 June 2008	No Seed	19:28 – 19:42	No
13 June 2008	Seed	20:04 – 20:15	No
13 June 2008	Seed	20:51 – 21:04	No
14 June 2008	No Seed	21:02 – 21:14	No
14 June 2008	No Seed	21:21 – 21:33	No
19 June 2008	Seed	21:53 – 22:06	No
21 June 2008	Seed	21:50 – 22:00	Yes
26 June 2008	No Seed	22:35 – 22:50	Yes (A)
26 June 2008	No Seed	23:03 – 23:15	Yes (B)
7 July 2008	Seed	23:56 – 00:04	No
9 July 2008	Seed	20:13 – 20:25	Yes

the seed/no seed decision is made. The cloud base sampling duration for no seed cases is 12 minutes, which is the same as the average time required to treat a candidate with 4 sets of flares (3 minutes burn time). The June 26 'No Seed' cases have differential reflectivity after time zero that drop sharply and then remain fairly constant, while the seed cases have a slow decrease with time. The differential reflectivity values exclude scans above the freezing level; therefore, only liquid drops affect the differential reflectivity. A field of large drops will tend to fall with an oblate orientation. The field of drops, as a whole, will have a larger cross-section of water in the horizontal compared to the vertical. Therefore, a horizontally-polarized radar pulse will be backscattered more than a vertically-polarized pulse which results in the differential reflectivity being greater than zero (Figure 10). If the zero time is at the same point in the cloud's life cycle, the seed cases produce larger drops longer than the no seed cases as is evident by the larger normalized differential reflectivity.

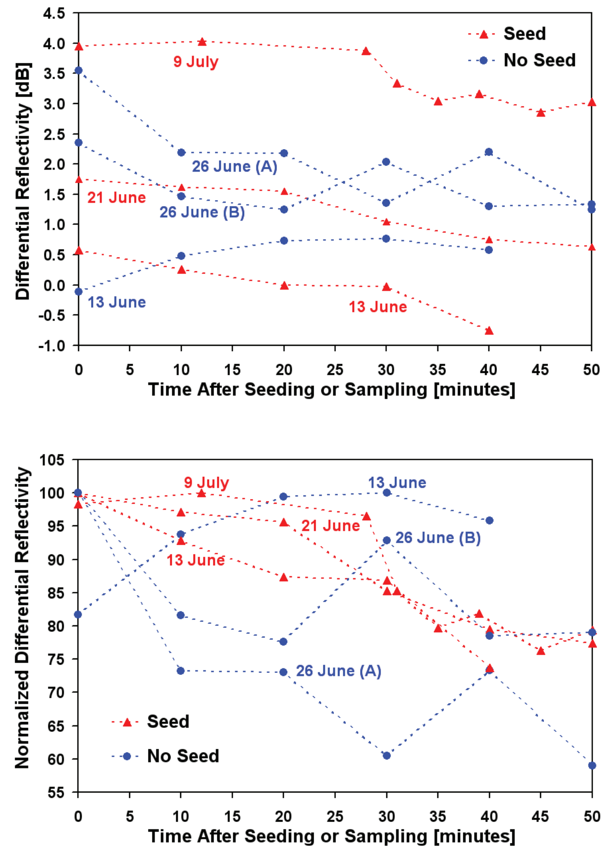

Figure 10: The time after seeding or sampling finished versus differential reflectivity and normalized differential reflectivity for POLCAST2's "area of influence" cases. Normalized Differential Reflectivity is calculated by dividing the differential reflectivity by the maximum differential reflectivity during the 50 minutes after seeding or sample. Radar measurements above the freezing level are excluded. Date labels correspond to cases summarized in Table 4. The 13 June cases do not include 50 minute data points since the area of influence does not include radar echoes at this time.

Figure 11 shows that five of the six cases had normalized rain rates that increased to a maximum and then decreased after seeding or sampling finished; and one case that started with a high normalized rain rate and then steadily decreased. Having a majority of cases where the normalized rain rates increase after seeding/sampling indicates that the clouds were being targeted early in their life cycle. Excluding the 13 June seed case, where the seeding probably occurred later in the cloud's life cycle, seed cases still had normalized rain rates that were higher than no seed cases; however, only the 9 July case had a rain rate significantly larger than the no seed cases. For the 9 July case, analysis of the hydrometeor type (using a polarimetric-based algorithm) indicates a significant fraction of hail/rain mix which is likely contaminating the rain rates resulting in higher than actual rain rates.

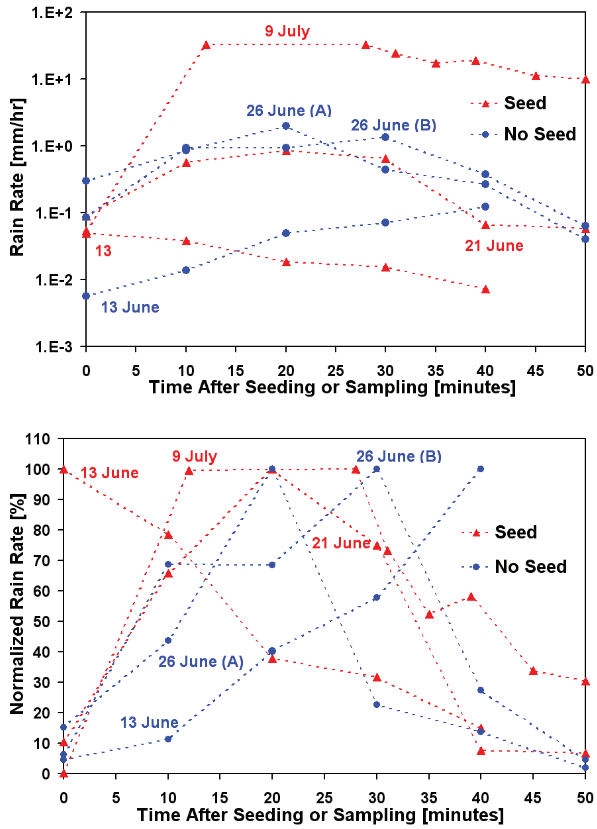

Figure 11: The time after seeding or sampling finished versus the rain rate (top) and the normalized rain rate (bottom) for POLCAST2's "area of influence" cases. The time interval's maximum rain rate is used to create the normalized rain rate. Date labels correspond to cases summarized in Table 4. The 13 June cases do not include 50 minute data points since the "area of influence" does not include radar echoes at this time.

With only six analysis cases, no conclusion about the effectiveness of hygroscopic seeding is possible. However, with a larger data set of cloud candidates, our analysis method could address seeding effectiveness. It is important to note that less than half (five out of thirteen) of the potential seeding candidates had "areas of influence" with sufficient radar echoes, so obtaining a sufficient number of cases is not just a question of finding candidates but having candidates that mature to produce drops large enough to be detected with C-band radar.

6. CONCLUSIONS

With the limited number of cases obtained during POLCAST2, it is impossible to draw any definitive conclusions about the effectiveness of hygroscopic seeding in North Dakota. However, the methodology of using polarimetric radar data to analyze "areas of influence" is promising for evaluation of possible seeding effects. Normalized differential reflectivity values decreased to low values sooner for non-seeded candidates than for seeded candidates which can be explained due to hygroscopic flare particles creating larger drops longer into the life cycle of seed clouds (Cooper et al., 1997; Yin et al., 2000). The 9 July seeded case had a higher rain rate at earlier times than the non-seeded candidates. This agrees with the Yin et al. (2001) cloud microphysical model results where seeded cases had significantly higher rain rates. However, this may simply be due to a hail contamination issue.

The aircraft data show that the cloud base aerosol and droplet concentrations are generally relatively high in summertime North Dakota, with CCN concentrations much higher than in other areas (Mali and Saudi Arabia) where similar measurements have recently been made. The cloud base aerosol concentrations are seen to vary from day to day which is important when evaluating the effectiveness of hygroscopic seeding. Measurements of cloud base aerosol properties will allow for seeding cases to be stratified into high and low aerosol concentration days.

Additional field measurements are necessary to increase the number of randomized cases and strengthen the results presented here on the effects of hygroscopic seeding in the North Dakota region. One advantageous method of analysis that should be done in further studies would be to use a polarimetric rain rate algorithm to provide more accurate values of radar estimated rain rate. This is important since contamination by hail/rain mix could significantly affect the difference between seeded and non-seeded rain rates and the interpretation of the effects of hygroscopic seeding.

It should be noted that with a highly successful field project, that had limited equipment problems, providing only six candidates for evaluation by radar, obtaining enough potential seeding candidates for any type of statistically meaningful results will require significantly more resources. Hence, focusing on understanding the physical processes involved with how hygroscopic seeding effects precipitation development in North Dakota may be the more productive research method.

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