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Statistical Analysis Of The Polarimetric Cloud Analysis And Seeding Test (Polcast) Field Projects

Jamie Ekness

STATISTICAL ANALYSIS OF THE POLARIMETRIC CLOUD ANALYSIS AND SEEDING TEST (POLCAST) FIELD PROJECTS

By

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This thesis, submitted by Jamie Ekness, in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota, has been read by the Faculty Advisory Committee under whom the work has been done and is hereby approved.

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Dean of the School of Graduate Studies

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Title	Statistical Analysis of the Polarimetric Cloud Analysis and Seeding Test (POLCAST) Field Projects.
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Jamie Ekness

July 18, 2017

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ABSTRACT

The North Dakota farming industry brings in more than $4.1 billion annually in cash receipts. Unfortunately, agriculture sales vary significantly from year to year, which is due in large part to weather events such as hail storms and droughts. One method to mitigate drought is to use hygroscopic seeding to increase the precipitation efficiency of clouds. The North Dakota Atmospheric Research Board (NDARB) sponsored the Polarimetric Cloud Analysis and Seeding Test (POLCAST) research project to determine the effectiveness of hygroscopic seeding in North Dakota. The POLCAST field projects obtained airborne and radar observations, while conducting randomized cloud seeding. The Thunderstorm Identification Tracking and Nowcasting (TITAN) program is used to analyze radar data (33 usable cases) in determining differences in the duration of the storm, rain rate and total rain amount between seeded and non-seeded clouds. The single ratio of seeded to non-seeded cases is 1.56 (0.28 mm/0.18 mm) or 56% increase for the average hourly rainfall during the first 60 minutes after target selection. A seeding effect is indicated with the lifetime of the storms increasing by 41 % between seeded and non-seeded clouds for the first 60 minutes past seeding decision. A double ratio statistic, a comparison of radar derived rain amount of the last 40 minutes of a case (seed/non-seed), compared to the first 20 minutes (seed/non-seed), is used to account for the natural variability of the cloud system and gives a double ratio of 1.85. The Mann-Whitney test on the double ratio of

seeded to non-seeded cases (33 cases) gives a significance (p-value) of 0.063. Bootstrapping analysis of the POLCAST set indicates that 50 cases would provide statistically significant results based on the Mann-Whitney test of the double ratio. All the statistical analysis conducted on the POLCAST data set show that hygroscopic seeding in North Dakota does increase precipitation. While an additional POLCAST field project would be necessary to obtain standardly accepted statistically significant results ($p<0.5$) for the double ratio of precipitation amount, the obtained p-value of 0.063 is close and considering the positive result from other hygroscopic seeding experiments, the North Dakota Cloud Modification Project should consider implementation of hygroscopic seeding.

CHAPTER 1

BACKGROUND

North Dakota has an area of 45 million acres with approximately 40 million acres, or 90 %, used for farming and ranching (Farm Flavor 2017). Impacts from hazardous weather, such as hail damage and loss of crops due to drought (Figure 1), affects the agricultural economy of the state (Ashenbrenner 2012). North Dakota has the highest crop insurance dollar loss in the country because of a history of crop damage (Smith et al. 1997). Annual losses due to hail, drought, and flooding range from millions to hundreds of millions of dollars for the state (NCSL 2008). North Dakota 2002 drought losses were $223 million and the 2006 drought losses were $425 million (NCSL 2008). The economic impact of North Dakota's crop loss affects the rest of the country, since North Dakota farmers produce 95 % of flax seed, 90 % of canola, and 56 % of pinto beans in the United States (North Dakota Department of Agriculture 2010).

Figure 1: An image showing effects of 2017 drought on North Dakota corn crops. Image is from http://www.agweek.com/news/nation-and-world/4280417-drought-conditions-lead-herd-trimming

One method to mitigate the damaging effects of hail and drought is to use a weather modification technique known as "cloud seeding" (AMS 2010). Cloud seeding is accomplished by releasing either ice nuclei or cloud condensation nuclei into clouds. Typically, ice nuclei are artificially generated using acetone generators, releasing dry ice, or burning flares. Introducing ice nuclei into clouds is done by either aircraft releasing material directly into cloud or into the updraft at cloud base, or ground based generators releasing material which is carried by the wind into the cloud.

Silver Iodide (AgI), an ice nuclei, has been used in cloud seeding operations since the 1950s for mitigating hail, improving visibility in super-cooled fog, and increasing precipitation amounts. Introduction of AgI causes supercooled liquid water droplets to freeze at warmer temperatures (WMA 2011), since AgI has an activation threshold near -4^{o} C (Braham 1959). The activation threshold of AgI is warmer than naturally occurring ice-forming nuclei that activate at -15^{o} C (ASCE and ASCE 2013). The small ice crystals that are nucleated grow by sublimation and riming (contact with droplets) to form precipitation-size ice crystals which reach the ground as either snow or rain.

The North Dakota Cloud Modification Project (NDCMP) uses AgI for hail mitigation (Smith et al. 1997) and increasing rainfall in several Western North Dakota counties (WMI 2016). The area of NDCMP (Figure 2) covers 7.4 million acres, 16 % of North Dakota (Weather Modification International 2016). Cost of the NDCMP was determined to be approximately 13 cents per acre (NDARB 2012) with a statewide cost of approximately $3 million per year providing benefits in the range of $95.4 million to $134.5 million annually

(Bangsund and Leistritz 2009). According to the 2016 NDARB Final Operations Report, a direct economic benefit in the counties taking part in the NDCMP range from $12 million to $19.7 million (5 % to 10 % increase in rain, respectively), and has a benefit-to-cost ratio of 16-to-1 up to 26-to-1 (Weather Modification Incorporated 2016).

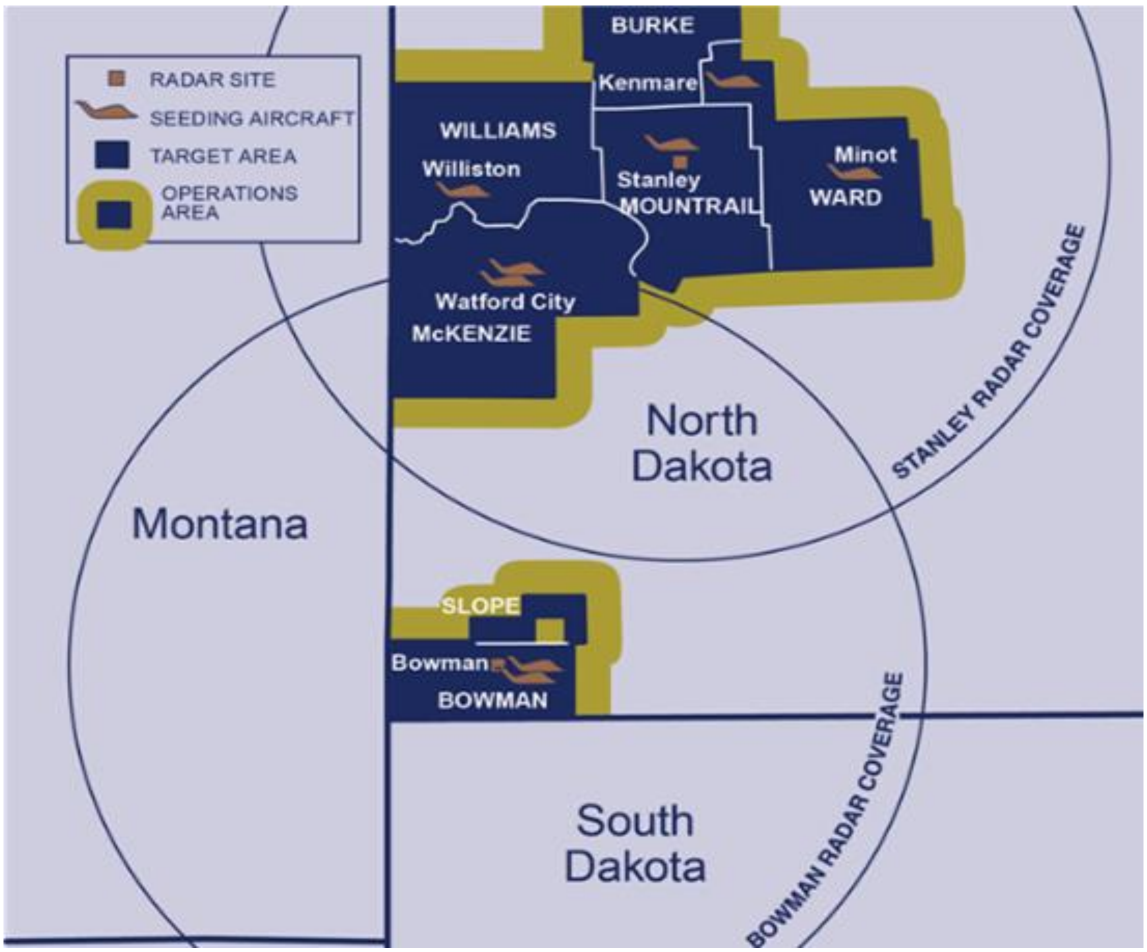


Figure 2: Map showing the location of the 2015 North Dakota Cloud Modification Project target areas (blue) and operational areas (blue and green) areas. The two larger circles indicate the radar coverage. The image is courtesy of the North Dakota Atmospheric Research Board. Image is found at https://secure.swc.nd.gov/arb/ndcmp/pdfs/finalreport.pdf.

Atmospheric particles can be cloud condensation nuclei (CCN), which provide a surface for water vapor condensation and cloud droplet activation. After activation, the droplets can grow to more than one hundred times their starting size (American Meteorological Society 1967). Hygroscopic seeding introduces CCN into the updraft of a cloud with a diameter greater than naturally occurring CCN (Bruintjes et al. 2012). The larger diameter CCN released into the cloud activate and grow by condensation at a lower supersaturation than smaller diameter CCN that occur naturally and results in clouds with larger cloud droplets (Mather et al. 1997; Aalto and Kulmala 2000). Growth by condensation was shown to be effective until the droplet reaches 30 to 50 µm in radius (Houghton 1950); therefore, growth above a radius of 50 µm requires the collision and coalescence process. The collision-coalescence process produces rain drops as large cloud drops bump (collide) into and bounce off or stick (coalesce) to smaller cloud droplets (Figure 3). The relative motion within the cloud allows droplets of varying sizes to collide and coalesce. Andronache (2002) show that the collection process of droplets into larger drops is efficient for droplets approximately ten microns or greater in diameter. If drops are of similar size, collisions would rarely occur since all drops would move at the same speed with respect to the airflow. Hence, precipitation formation by collision and coalescence is more efficient with a wider drop size distribution (Johnson 1982; Mechem 2006). Therefore, the larger CCN introduced by hygroscopic seeding lead to more efficient precipitation formation, specifically in continental areas which have a higher concentration of small, accumulation sized particles (approximately 0.1 µm -2.0 µm) and few large CCN present to initiate the collision and coalescence process (Yin et al. 2000).

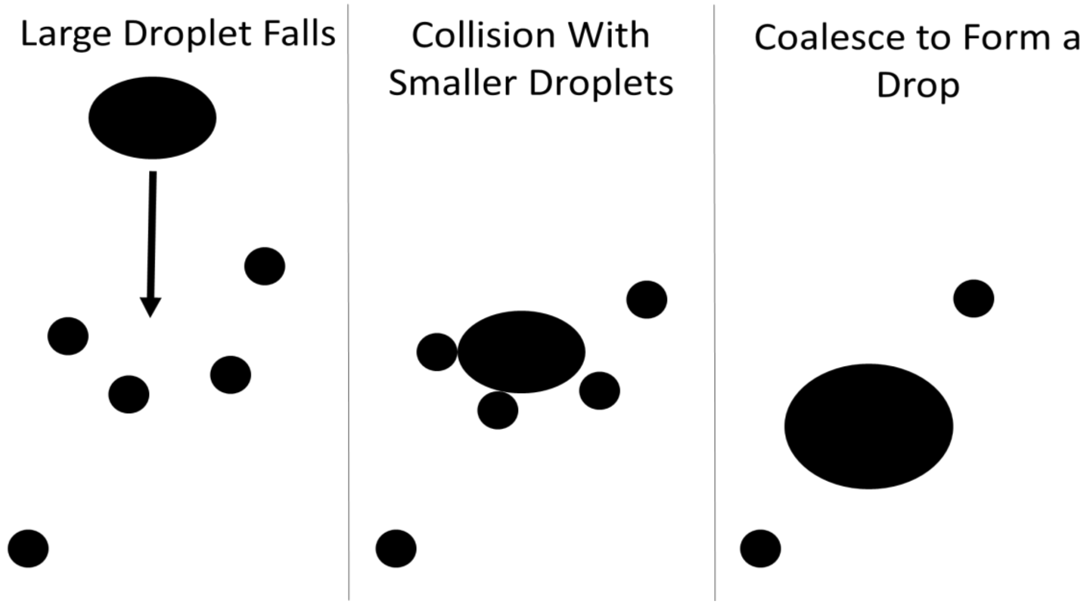
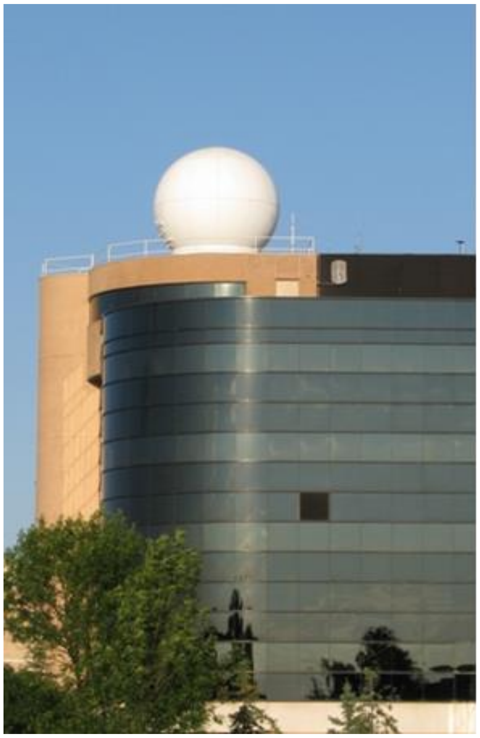


Figure 3: An image showing a simple example of the collision and coalescence process.

Hygroscopic seeding has been done intentionally and unintentionally in regions around the world (Bruintjes 1999). In South Africa, unintentional seeding was observed to produce precipitation downwind of a Kraft Paper Mill (Mather et al. 1997). A Learjet with cloud physics equipment onboard sampled clouds downwind of the Kraft Paper Mill and observed drops with diameters of 4-6 mm within a strong updraft of 10 to 15 m/s. Within clouds affected by the Paper Mill, there was a broader cloud droplet spectra than clouds not affected by the Paper Mill, due to the release of hygroscopic particles (Mather et al. 1997). In addition to the increase in drop size distribution, clouds influenced by the Paper Mill lived longer than those not affected (Mather et al. 1997). Similar results were found from randomized seeding experiments in Mexico when larger CCN were introduced into growing convective clouds (Silverman 2010). Longer-lived clouds, as seen in South Africa and Mexico, can result from dynamic effects and not just a direct seeding effect. When precipitation occurs earlier and lower in the cloud, a stronger downdraft close to the updraft can occur (Silverman and Sukarnjanaset 2000). The dynamic interaction between the inflow and gust front initiate cloud growth (Silverman and Sukarnjanaset 2000) and can keep the seeded cloud 'alive'.

Positive outcomes from the South Africa and Mexico randomized seeding experiments led to a data collection and analysis project in North Dakota. Four Polarimetric Cloud Analysis and Seeding Test (POLCAST) field projects were conducted in Eastern North Dakota during the summers of 2006, 2008, 2010, and 2012 (Kucera 2012). The POLCAST field projects seeded convective clouds with hygroscopic flares to determine the effect on precipitation and validate the conceptual model of hygroscopic seeding (Kucera et al. 2008). The 2006 POLCAST field project seeded target clouds with hygroscopic flares to determine if changes in cloud properties (e.g. reflectivity) observed by the University of North Dakota (UND) polarimetric radar (NorthPol) (Figure 4) could be detected. In 2006, eight target clouds were seeded with flares, of which seven showed an increase in radar estimated liquid water content (Kucera et al. 2008). With positive results in 2006, additional projects were conducted during the summers of 2008 (POLCAST2), 2010 (POLCAST3), and 2012 (POLCAST4) which included random seeding of cloud targets. Random seeding allows for an unbiased comparison of seeded and non-seeded clouds to determine difference in precipitation amounts as observed by radar.



Reflector Type	Parabolic Dish
Dish Size	3.66 m
Wavelength	5.4 cm
Frequency	5600 MHz
Minimum Detectable Signal	-106.5 dB

Figure 4: An image showing the white dome of the NorthPol radar located on the Clifford Hall rooftop at the University of North Dakota in Grand Forks, North Dakota. The specifications of the NorthPol radar are given in the table.

In the 2008 study (POLCAST2), 13 cloud targets were obtained: seven seed and six non-seed (Delene et al. 2011). Each of the 13 targets were sampled using aircraft instruments that measured environmental factors such as cloud base CCN concentration, cloud base temperature, and cloud base altitude (Delene et al. 2011). Radar data was recorded to determine rainfall amounts using the Thunderstorm Identification Tracking and Nowcasting (TITAN) program. TITAN was used to analyze radar reflectivity and track the progression of cloud targets. Analysis indicated that for seeded cases, normalized differential reflectivity decreased to low values sooner due to hygroscopic seeding particles creating larger drops later in the life cycle of the cloud (Delene et al. 2011). A POLCAST field project was conducted in 2010 and 2012 which resulted in a combined data set of 44 total cases. The POLCAST data set is analyzed to determine if hygroscopic seeding is effective and what number of cases are required for statistically significant results.

CHAPTER II

POLCAST DATASET

For each POLCAST project, Weather Modification International (WMI) used a Cessna 340 aircraft to conduct seeding and airborne measurements. During POLCAST2, WMI operated a Cessna 340 with registration number N37360. POLCAST3 began with a Cessna 340 (N37356), but because of engine issues ended the project using N37360. The Cessna 340 with a registration number of N98585 was operated by WMI during POLCAST4. Flare racks mounted on the wings of the aircraft (Figure 5) each held 12 hygroscopic flares provided by Ice Crystal Engineering (ICE).

Figure 5: Image showing the Cessna 340 aircraft used during POLCAST2 and the end of POLCAST3 located at the Fargo Jet Center in Fargo, North Dakota. Shown on the right is an image of one wing with a full set of hygroscopic flares. Both images were taken during POLCAST3.

The Cessna 340 aircraft also made atmospheric measurements with instruments that included the Passive Cavity Aerosol Spectrometer Probe (PCASP), Forward Scattering Spectrometer Probe (FSSP), University of Wyoming (UWyo) Cloud Condensation Nuclei Counter (CCNC), Rosemount temperature probe, hot wire probe, GPS, Edgetech hygrometer, and the Aircraft Integrated Meteorological Measurements System (AIMMS) probe. The Science Engineering Association (SEA) model M300 Data Acquisition System (DAS) operated by an on-board flight engineer collects all aircraft measurements. The UWyo CCN is run at 1.0 % supersaturation (ambient supersaturation of ~0.6 %) for all POLCAST flights. The AIMMS probe, only used during the last five flights of 2012, measures three-dimensional winds and determines the vertical velocity below the cloud. The AIMMS probe updraft measurements obtained during POLCAST4 agreed with the pilot's estimated updraft velocity (Simelane et al. 2013).

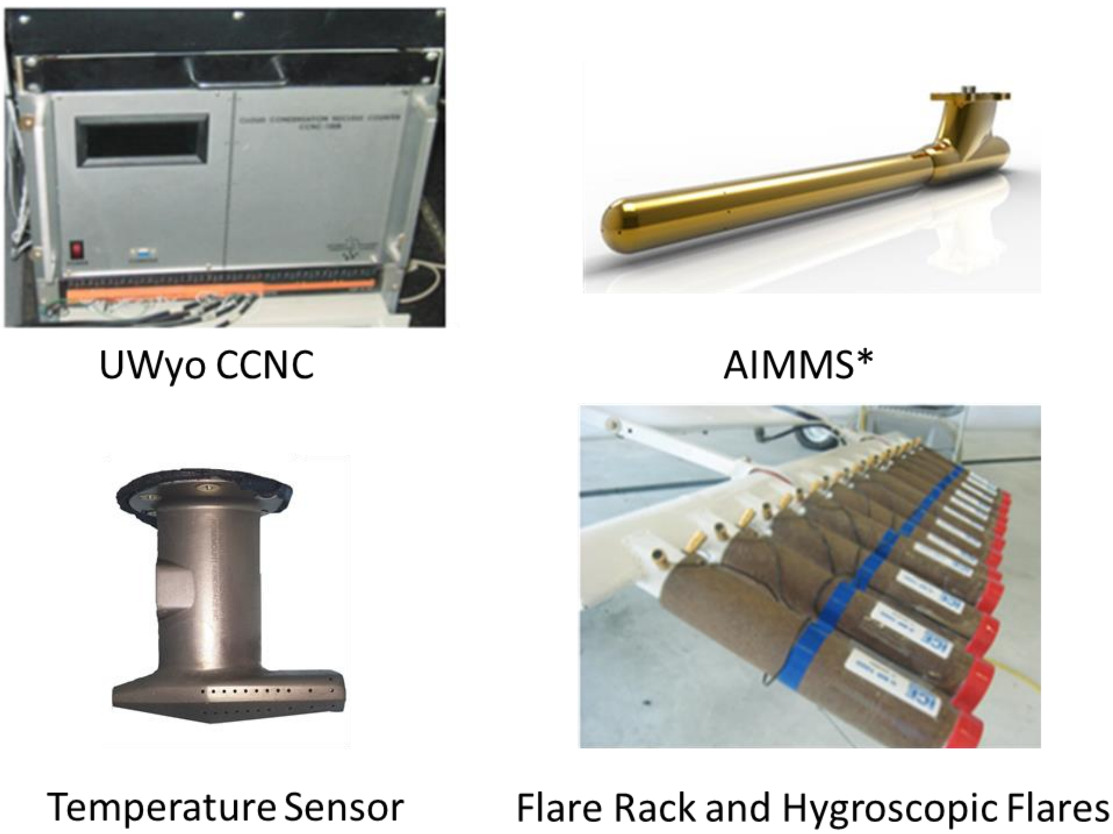


Figure 6 Important instruments included on the Cessna 340 aircraft used to make atmospheric measurements during the Polarimetric Cloud Analysis and Seeding Test (POLCAST) field projects specific to this study. *The AIMMS probe measurements are only available for the last five cases of POLCAST4. The pressure transducer is not shown.

The POLCAST data set consists of 44 cases (Figure 9) from 2008 (13 cases), 2010 (14 cases), and 2012 (17 cases) which were randomly seeded. Prior to the start of POLCAST2 in 2008, the science teams defined target specifications to ensure that similar clouds were selected. Target clouds were required to have an updraft of around 500 feet/min, a rain free base, a cloud base temperature between 0 ^{o}C and 20 ^{o}C, and evidence of cloud top growth in the early stage of cloud development (National Center for Atmospheric Research et al. 2008). When a target cloud was located during a POLCAST flight, an envelope was opened at the operations center in Grand Forks to reveal the seed or non-seed decision (Figure 7) Decisions were predetermined before the POLCAST2 project and envelopes with seed and non-seed cases randomly distributed, but no more than four of the same case occurred consecutively. For each seed case called, two flares are ignited (one on each wing). When flares show signs of burning out, another set is ignited until a total of four sets (8 flares) are dispensed, which takes approximately 12 minutes. The aircraft circles below cloud base for 12 minutes after a seed decision is called to define an area of influence (Figure 8) which is used during the radar analysis. Cloud base environmental factors (CCN, temperature, and pressure altitude) are measured by instruments on the aircraft as seeding is being conducted. Due to instrumentation issues and test flights, only 37 of the 44 cases (Figure 9) are available for statistical analysis.

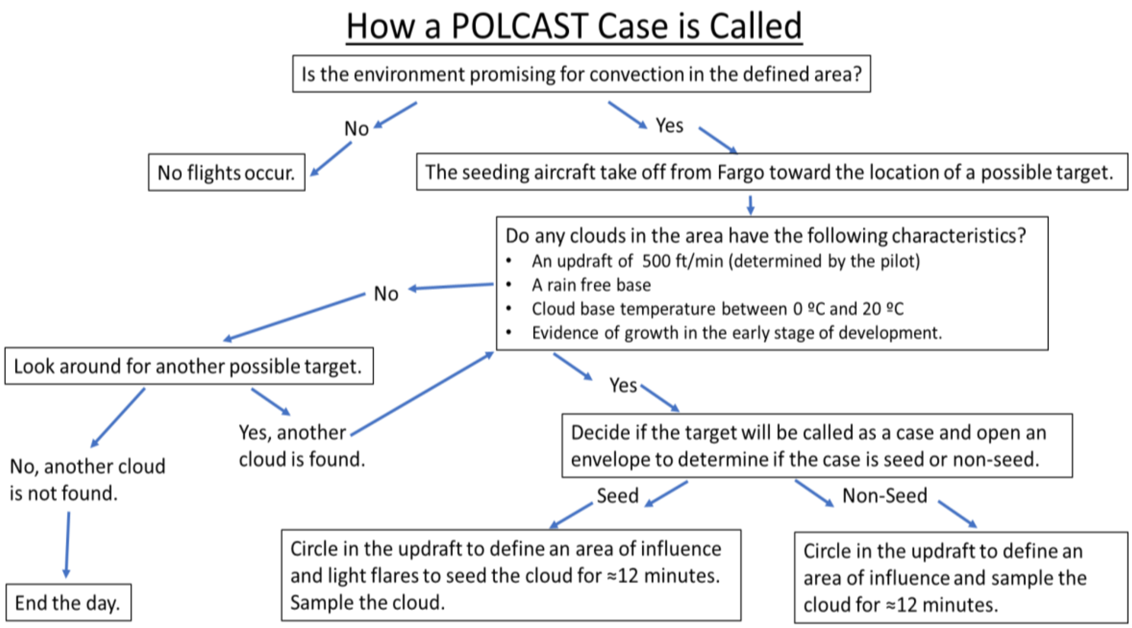


Figure 7: A flow diagram showing how a case is called during the Polarimetric Cloud Analysis and Seeding Test (POLCAST) projects.

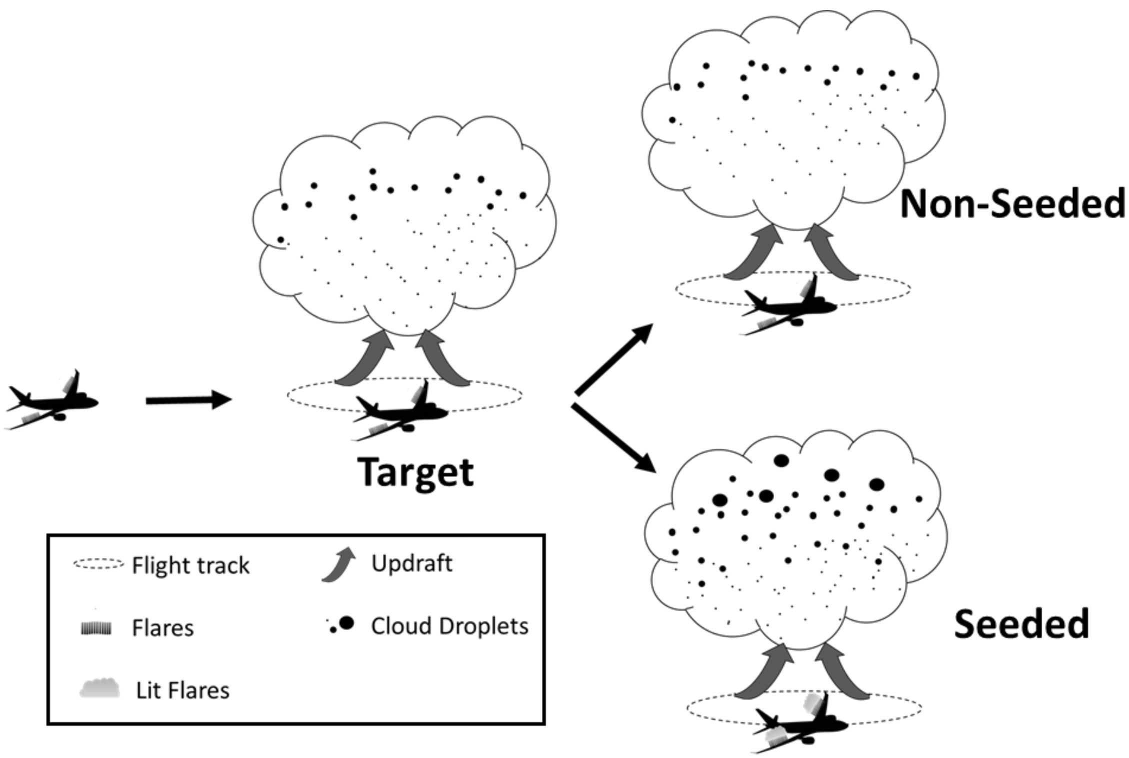


Figure 8: Schematic showing the different flight pattern for a seed and non-seed decision. The aircraft either seeds (lower right) or does not seed (top right) a target. In either case the aircraft circles to define an area of influence, which is shown by the dashed ellipse. Black dots within the clouds represent cloud droplets.

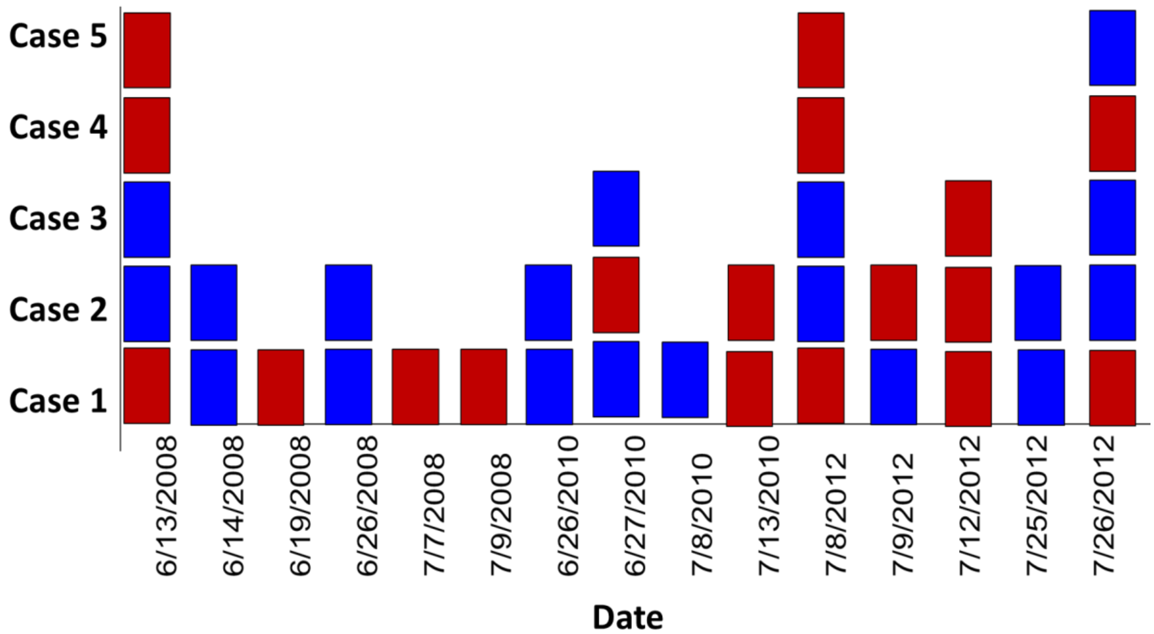


Figure 9: The date and ordering of cases for 2008, 2010, and 2012, with the first target on the bottom. Each box represents a case, seeded (red) and non-seeded (blue).

As the aircraft conducts seeding and sampling, the UND C-Band Dual Polarization Doppler Radar (NorthPOL) (Figure 4) is operated by a radar scientist who communicates with aircraft personnel. Seeding is only conducted in North Dakota (Figure 10); however, clouds are tracked into Minnesota up to 60 minutes after the 12 minutes' area of influence is defined or until the storm dies. Figure 10 summarizes the POLCAST targets.

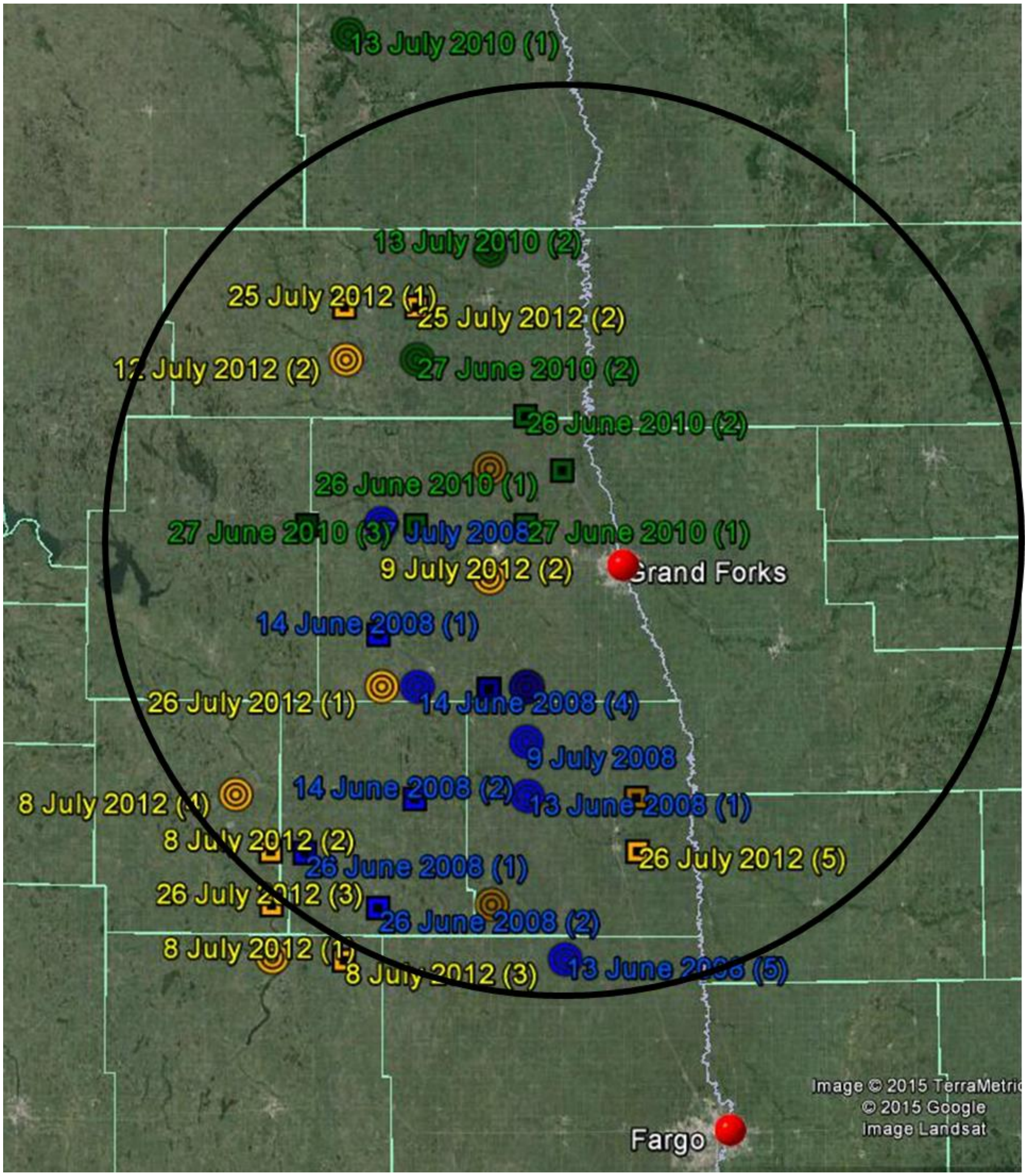


Figure 10: An image showing the study area of POCLAST. The black circle is the 100-km radius around the University of North Dakota (UND) radar. Cases for 2008 (blue), 2010 (green), and 2012 (yellow) are shown with the circles representing hygroscopic seed cases and the squares representing non-seed cases. The jagged white line image is the North Dakota/Minnesota border.

The volume scanning mode with 16 tilts and a max elevation of approximately 22° is standard radar operations during POLCAST. The radar rotates 360° at one elevation before moving to the next elevation to fill the scan volume. During POLCAST4, scanning includes sector scans where the same elevation tilts were used as in a 360-degree volume scan, but within a smaller azimuth angle. The sector scans focus radar observations on the cloud of interest to provide observations within a shorter sampling time. Of the 37 valid hygroscopic cases obtained from the POLCAST projects, 33 cases (16 non-seed and 17 seed) have reflectivity and tracking information necessary for statistical analysis of precipitation.

CHAPTER III

METHODOLOGY

To evaluate the POLCAST data set, statistical tests are used to determine hygroscopic seeding effects on precipitation. Specifically, the following questions are addressed.

- Are seeded and non-seeded clouds homogeneous with respect to cloud base environmental factors?
- How does hygroscopic seeding affect North Dakota precipitation?
- How many cases are needed to show statistically significant results on the effect of hygroscopic seeding?

To investigate cloud base environmental factors (Cloud Condensation Nuclei (CCN) concentration, temperature, and pressure altitude) of the seeded and non-seeded clouds, the nonparametric Mann-Whitney test is used to assess whether there are significant differences between the seeded and non-seeded targets. To study the proportional effect of seeding and determine similarity between the seeded and non-seeded cases, single ratio statistics are computed (Gabriel 1999). In addition, double ratio statistics are used to account for differences between cases, such as calling a case at a different time during the life cycle of the cloud.

MANN-WHITNEY

The Mann-Whitney test is the non-parametric version of the t-test for independent samples and useful when comparing non-normally distributed populations using small data sets (Muralikrishna 2009), like the POLCAST data set. When comparing two population means using the Mann-Whitney test, it is assumed that the two samples of data are independent random samples from a continuous distribution that have the same shape and spread with the only possible difference between the two being in the population means (Devore and Berk 2012). Since a random procedure was used to determine if a given cloud was to be seeded or not, it can be assumed that the seeded and non-seeded clouds represent random samples. It is reasonable to assume that the distributions of the environmental factors would be similar except possibly for shifts in their centers between the seeded and non-seeded clouds. The Mann-Whitney test is an appropriate tool for determining if there are significant shifts in the center of the seeded and non-seeded populations of the cloud base environmental factors of interest (temperature, pressure altitude, and CCN concentration), which would indicate non-homogeneity of the seeded and non-seeded populations. The environmental factor mean measurements from the seed and non-seed data sets are combined and ranked (low to high), with ties accounted for. The ranked data is re-sorted back into their respective data sets to be used in the Mann-Whitney equation, given by:

$$U_1 = n_1 n_2 + \frac{(n_1(n_1+1))}{2} - \sum_{i=n_i+1}^{n_i} R_i \quad (1)$$

The Mann-Whitney U test statistic is represented by U_1, n_1 and n_2 represent the sizes of the two samples, and R_i represents the rank of sample 1. Extreme values of U_1, either large of small, would lead to the rejection of the null hypothesis of equal means and cast doubt on the homogeneity of the seeded and non-seeded populations with respect to environmental factors. By having populations of cases with similar environmental factors, the effects of seeding, increased rain amount and rain rate, can be determined without the environmental factors considered influencing the results.

SINGLE RATIO AND DOUBLE RATIO

The single ratio statistic is used to assess the magnitude of the effect of cloud seeding on precipitation and is given by:

$$\text{Single Ratio} = \frac{\text{Seed}_{\mathbf{A}}}{\text{Non}-\text{Seed}_{\boldsymbol{A}}} \tag{2}$$

where A represents a given measurement of interest and *Seed*$_A$ *and Non-Seed*$_A$ represent the average values of measurement A for the seeded and non-seeded cases, respectively. A single ratio greater than 1.0 indicates a positive effect of seeding on measurement A. The single ratio is used to analyze seeding effects on rain rate and rain amount using the seed and non-seed cases from the POLCAST data set.

The relative impact of cloud seeding on measurement A is compared using the double ratio equation given by:

(3)

during the 30 minute to 60-minute (final four radar scans) period following conclusion of aircraft circling to define the area of influence, denoted X, to that observed during the 10 minute to 20-minute period (first two radar scans), denoted Y, for the samples of seed and non-seed cases. The double ratio takes into account the variability between the seeded clouds and non-seeded clouds by normalizing the parameter over the first 20 minutes. A large value of the double ratio statistic indicates a greater impact of cloud seeding on measurement A is occurring during the 30 to 60 min period.

TITAN

TITAN (Thunderstorm Identification Tracking and Nowcasting) was created by Mike Dixon of UCAR in the 1980's and is a software using radar data for detailed analysis. The main purpose of the original TITAN was to determine effects of seeding convective clouds during a project conducted in South Africa (Dixon and Wiener 1993). TITAN has since expanded to include forecasting and statistical aspects, allowing for a more robust analysis of radar data (Dixon 2005). The current version, TITAN5, includes long term analysis and storm climatology (NCAR 2016). TITAN is a useful tool due to the adaptability of the software to analyze multiple types of radar data, as well as the ability to be user and project specific. Scripts are included in TITAN for converting radar data, tracking storms, overlaying aircraft tracks, adding winds, and considerably more. Parameter files for each of the scripts can be adapted by the user to output research specific data. Description of scripts used in the analysis of the POLCAST radar data are included in Table 1.

Table 1: Thunderstorm Identification Tracking and Nowcasting (TITAN) scripts used in analysis of the POLCAST data set. The description and output parameters for each script are included.

Script	Description	Parameters
Dsr2Vol	Reads from FMQ (file message queue) which stores data first in, first out and writes beam by beam radar data to an MDV (Meteorological Data Volume File) to be used in TITAN.	Radar images: DBZ, ZDR
Sigmet2Dsr	Takes the raw radar data and converts it to the DSR format. Used in combination with Dsr2Vol	Radar Images
Titan	Inputs MDV radar data created by Dsr2Vol and Sigmet2Dsr. Reads the data fields from the input file: reflectivity fields, identifies storms, precipitation fields.	Reflectivity, storms, precipitation
Tstorms2Symprod	Reads TITAN storm data files and converts to spdb format.	Radar Images – Track Storms
Ctrec	Tracks echo motion using a cross-correlation technique to match pattern movement. Output U/V fields in MDV format.	Winds
EsdAcIngest	Reads in aircraft data from an ASCII file and stores aircraft tracks as spdb.	Aircraft Tracks
AcTrack2Polygon	Reads ac_posn (aircraft position) data points created by EsdAcIngest and radar data to create a convex hull around the points of the	Polygon drawn around aircraft tracks

	aircraft track. (a specific length of time can be stated)	
AdvectPolygon	Creates a circle with centroid of a polygon as its center. Uses average winds (from ctrec) in the circle to advect the polygon (a specific length of time can be stated).	Advects and tracks a polygon while monitoring average rain rate.

TITAN is used to analyze the POLCAST radar reflectivity (dBZ) and rain rate. A difference between clouds seeded with hygroscopic flares compared to non-seeded clouds is expected, due to radar derived parameters (dBZ, Zdr) being altered by seeding (Yin et al. 2001). To evaluate clouds sampled and seeded with hygroscopic flares compared to clouds only sampled (non-seeded), an area of influence (circle path under the updraft) is defined by the aircraft when a case is called. TITAN has the capability to define the area of influence by overlaying a polygon around the aircraft track for the 12 minutes of seeding/sampling, and track the polygon over time (Figure 11). The size of the area of influence does not change as the cloud grows, but is tracked along with the storm. Having the area of influence remains the same provides a better comparison between seed and non-seed cases since only the area of the storm known to be affect by the seeding is tracked instead of the whole storm. Each POLCAST seeding target is analyzed up to 60 minutes after the area of influence polygon is defined, or until the storm is no longer observable by radar. To convert reflectivity to rain rate, the Marshall-Palmer equation is used and average rain rate and total rain amount is calculated within the area of influence.

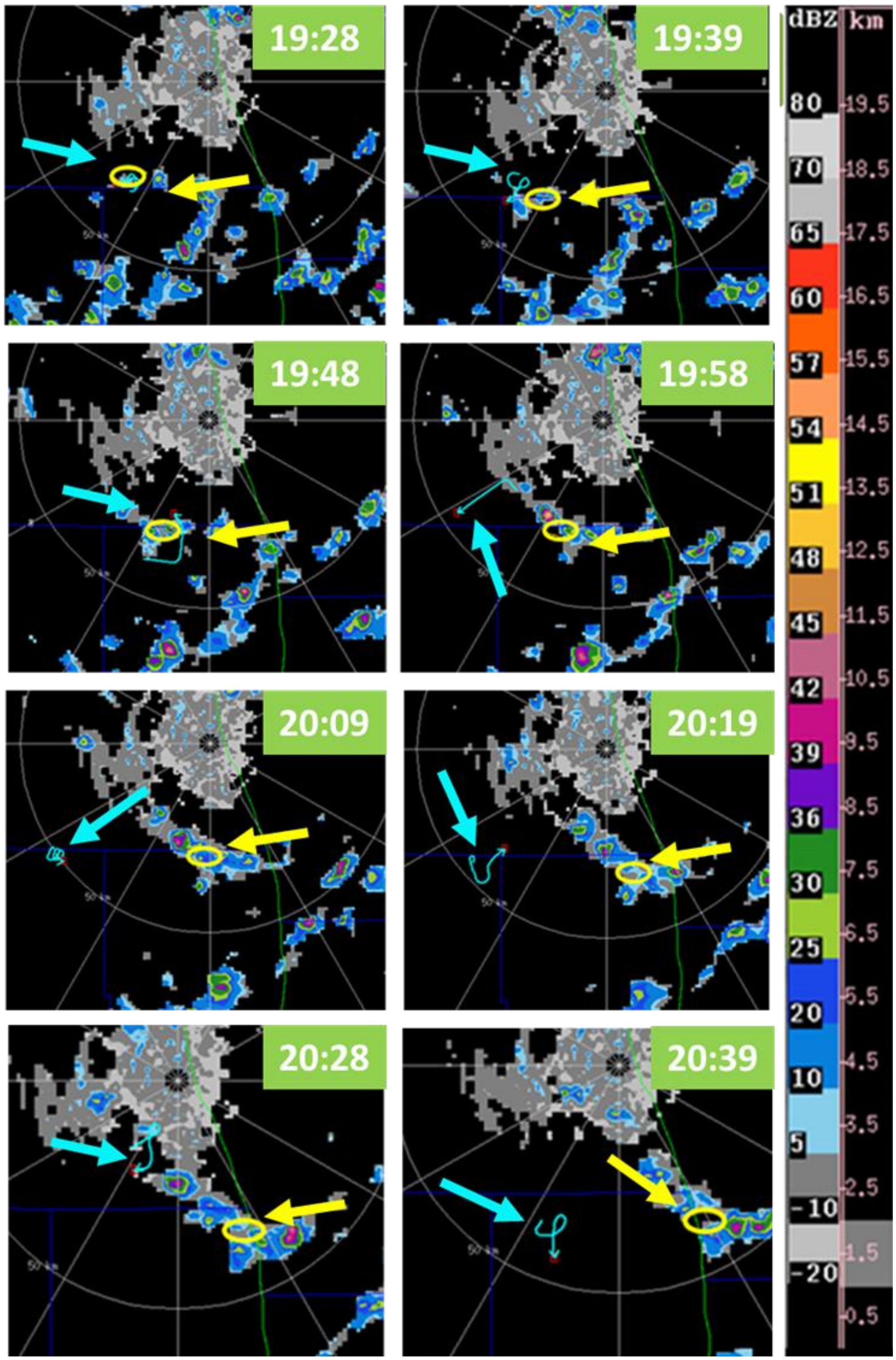


Figure 11: Image showing the radar reflectivity from a non-seed case on June 13, 2008. The aircraft track is shown by the teal arrow and teal line with the area of influence represented by the yellow ellipse and yellow arrow.

TITAN displays data in the Cartesian coordinate plane using the MDV (meteorological data volume) files created from raw Sigmet formatted data files using the Sigmet2Dsr and Dsr2Vol scripts. The Python code, convert_mdv, automates execution of the conversion scripts enabling processing of a whole field project. Some cloud targets have cloud drops that do not develop large enough to reflect energy back to the radar to give a return and the area of influence is shown as ‘empty’. Four targets from the field projects had no radar return within the area of influences and are excluded from analyzed cases, which reduces the number of cases from 37 to 33. Aircraft tracks displayed over TITAN radar images are created using the program POLCAST_air_tracks, while the PrecipAccum script provides total precipitation and aircraft tracks are provided by EsdAcIngest. A flow diagram of the complete POLCAST analysis is shown in Figure 12.

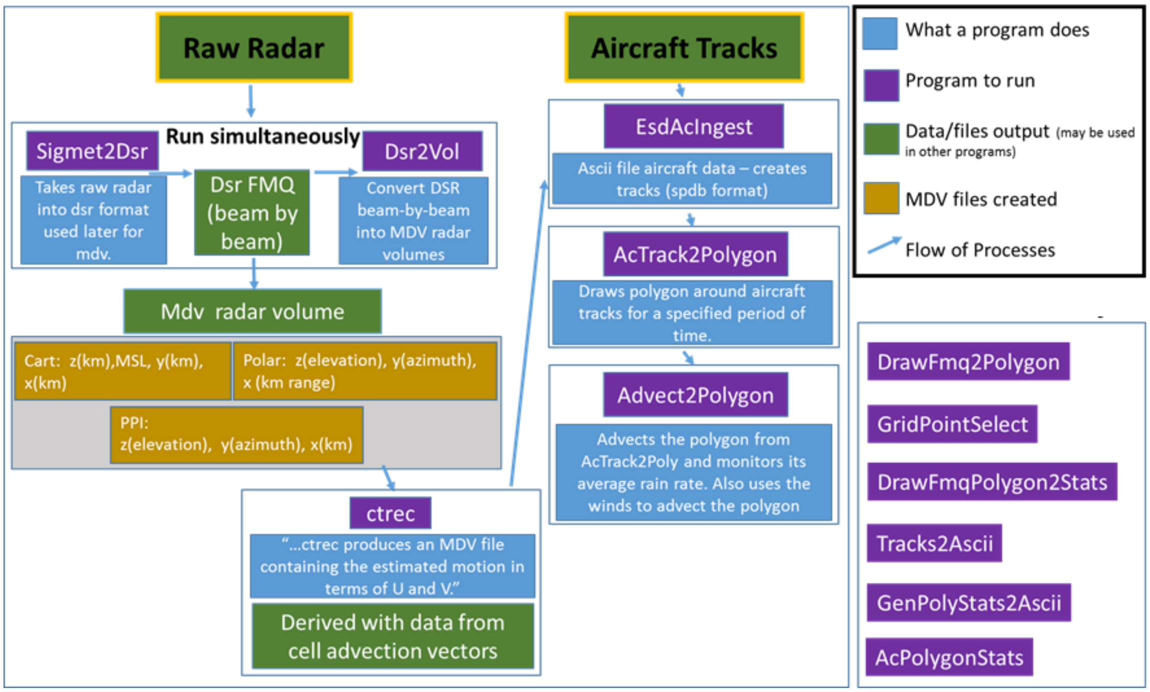


Figure 12: Flow diagram of the TITAN scripts used in the POLCAST data analysis. Purple shows the program name, blue shows the program description, green shows the data file, and blue arrows show how the programs are connected.

TITAN displays dBZ values from -20 to 80 dBZ; values below zero can be considered clutter and not relevant to the analysis. Values of dBZ within the area of influence are evaluated as clouds grow and move over time to allow for a comparison of seeded and non-seeded cases. In some cases, winds data was unavailable causing the polygon to track off course within the TITAN display, moving the area of influence to a location not physically possible; therefore, tracking the storm is done by the user. A complete list of cases analyzed by TITAN are included in Table 2 with Initial Cell indicating if there was reflectivity a return seen on radar before seeding a target cloud and Echo indicates a signal returned back to the radar which contains information about the location and distance of the storm.

Table 2: Date and type of case (seed or non-seed) that was analyzed by TITAN.

Date	Type of Case	Initial Cell	Echo
6/13/2008	Seed	No	Yes
6/13/2008	Seed	Yes	Yes
6/13/2008	Non-Seed	No	Yes
6/13/2008	Non-Seed	No	Yes
6/14/2008	Non-Seed	No	Yes
6/21/2008	Seed	Yes	Yes
6/26/2008	Non-Seed	Yes	Yes
6/26/2008	Non-Seed	No	Yes
7/9/2008	Seed	Yes	Yes
6/27/2010	Seed	Yes	Yes
6/27/2010	Non-Seed	Yes	Yes
7/13/2010	Seed	Yes	Yes
7/13/2010	Seed	Yes	Yes
7/19/2010	Seed	No	Yes
7/19/2010	Non-Seed	No	Yes
7/20/2010	Seed	Yes	Yes
7/20/2010	Non-Seed	No	Yes
7/20/2010	Non-Seed	No	Yes
7/8/2012	Seed	Yes	Yes
7/8/2012	Seed	Yes	Yes
7/8/2012	Seed	Yes	Yes
7/8/2012	Non-Seed	Yes	Yes
7/8/2012	Non-Seed	Yes	Yes
7/12/2012	Seed	Yes	Yes
7/12/2012	Seed	Yes	Yes
7/12/2012	Seed	Yes	Yes
7/25/2012	Non-Seed	No	Yes
7/25/2012	Non-Seed	No	Yes
7/26/2012	Seed	Yes	Yes
7/26/2012	Seed	No	Yes
7/26/2012	Non-Seed	No	Yes
7/26/2012	Non-Seed	Yes	Yes
7/26/2012	Non-Seed	Yes	Yes

BOOTSTRAPPING

The Bootstrapping Method is a resampling statistical technique that cycles through a data set to create a new data set with a user specified number of values. Bootstrapping cycles through the data set randomly selecting dates, so there is no guarantee of what combination of data will result. The randomness allows for a representation of possible future field projects and what the outcomes could be. The new data set could contain a value from the original data set only once, multiple times, or not at all after resampling (Miller). The Bootstrapping Method is applied to the data set of radar derived rain amount from the 33 POLCAST cases to create larger data sets. Rain amount (mm) is used as a variable to create bootstrapped data sets, because seeding clouds is done during POLCAST to produce more measurable precipitation; therefore, seeded cases would be expected to produce more rain than non-seed clouds. Analysis of rain amount allows comparison between seed and non-seed cases to determine if there is an increase in the amount of rain from the seeded targets. The double ratio is done to account for natural variance. In other research projects conducted in Thailand and Tasmania (Australia), (1960-2005) (Silverman and Sukarnjanaset 2000) (Morrison et al. 2009), there has been a control location or data set to use in comparison. During POLCAST, there was not a control – only seed and non-seed cases.

Table 3: Radar derived rain amount in millimeters calculated using an adapted Marshall-Palmer relationship within the area of influence for the POLCAST data set. The average and total for the seed and non-seed data sets are shown.

	Seed (Avg)	Seed (Total)	Non-Seed (Avg)	Non-Seed (Total)
10 minutes	0.050	0.858	0.043	0.684
20 minutes	0.075	1.127	0.039	0.553
30 minutes	0.061	0.919	0.029	0.290
40 minutes	0.060	0.776	0.027	0.242
50 minutes	0.044	0.523	0.030	0.151
60 minutes	0.046	0.323	0.029	0.116
Avg Rain Amt	0.275	4.671	.177	2.827

Two python scripts (one for all three years and the other for only 2012) are used to bootstrap the original POLCAST data set of rain amount. The scripts

Ratio_RainAmt_POLCAST_'I'.py and *Ratio_RainAmt_POLCAST2012_'I'.py* use the 33 successful radar cases to create data sets of 66, 132, and 264 cases. The Mann-Whitney test is applied to the double ratio of the bootstrapped data set to calculate the significance. The average significance from the Mann-Whitney for 10,000 iterations for each set of 66, 132, and 264 bootstrapped data sets gives the expected significance for each number of cases. Hence, the effect seeding has on rain amount and the number of cases needed for statistical significance is determined.

CHAPTER IV

DATA AND DISCUSSION

POLCAST field projects took place to gain an understanding of hygroscopic seeding effects on precipitation formation. In comparison to the total number of clouds observed in the POLCAST study area, the number of clouds considered as cases is small since target clouds had to meet predetermined requirements prior to being chosen. Cloud targets had to have an updraft of approximately 500 ft./min, a rain free base, cloud base temperature between 0^{o} C and 20^{o} C, and evidence of growth in the early stage of development (National Center for Atmospheric Research et al. 2008). By having such tight restrictions, the number of targets is reduced; however, a high-quality data set, even with fewer samples, provides more statistically significant results.

The North-Eastern corner of North Dakota is the POLCAST study area which likely has environmental factors such as CCN concentration, altitude, and pressure measurements similar to Western North Dakota. The CCN concentrations measured during the POLCAST project are between 300 #/cm^3 to 3000 #/cm^3. Modeling studies indicate hygroscopic successful seeding occurs when the CCN concentration is above 500 #/cm3 (Yin et al. 2000). The cloud base CCN concentration may affect hygroscopic seeding effectiveness or the effectiveness of precipitation development in general so it is important to known that each set (seeded and non-seeded) has similar properties to ensure differences are not due to differences in CCN concentration. The altitude of the cloud base determines the distance a droplet would have to fall to reach the surface; if the altitude is too high, the droplet could evaporate before reaching the surface. North Dakota cloud base altitude during the POLCAST projects ranges from 700 m to 2700 m. Cloud base temperatures measured during POLCAST range from 4º C to 22º C. The temperature gives an indication if ice would be present at a higher altitude or non-existent in the cloud. Measuring the environmental factors of each cloud allows for two subsets of the population, target (seed) and control (non-seed) POLAST cases. A complete statistical analysis can be done on the POLCAST data set to compare seed and non-seed cases.

Cloud base environmental factors (CCN, temperature, and altitude) measured during the POLCAST projects are evenly distributed between seed and non-seed cases. Figure 13 to Figure 16show mean values and intervals within one standard deviation of the mean for environmental factor measurements of seed (red) and non-seed (blue) cases. The distribution of cloud base measurements for the combination of POLCAST2, POCLAST3, and POLCAST4 (37 CASES) is shown in Figure 13. . Measurements of environmental factors for each project are displayed in Figure 14 (cloud base temperature), Figure 15 (cloud base CCN), and Figure 16 (cloud base pressure altitude) comparing seed and non-seed case.

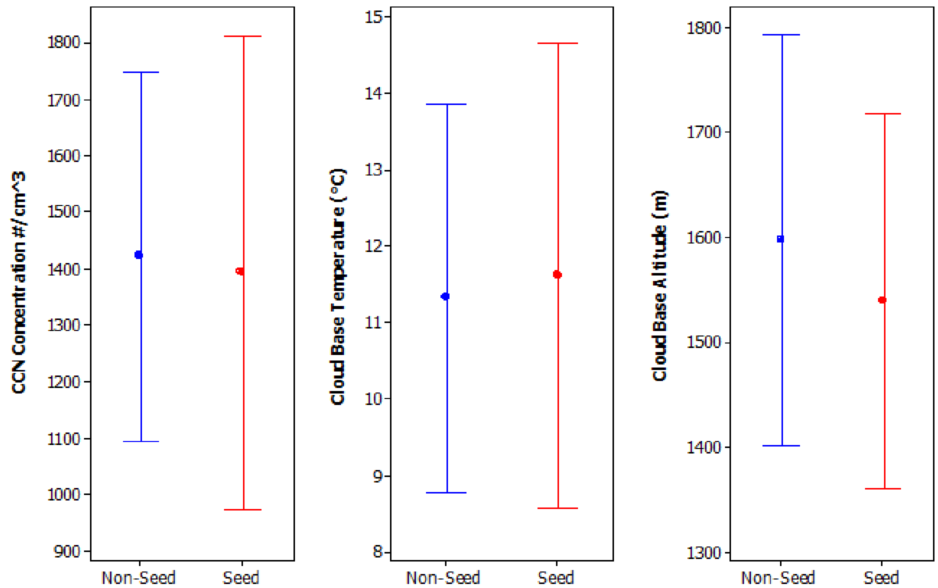


Figure 13: North Dakota measurements of cloud base cloud condensation nuclei concentration, temperature, and altitude for the POLCAST data set (2008, 2010, and 2012). The bars (above and below) represent one standard deviation of the mean. Red represents seed cases and blue represents non-seed cases.

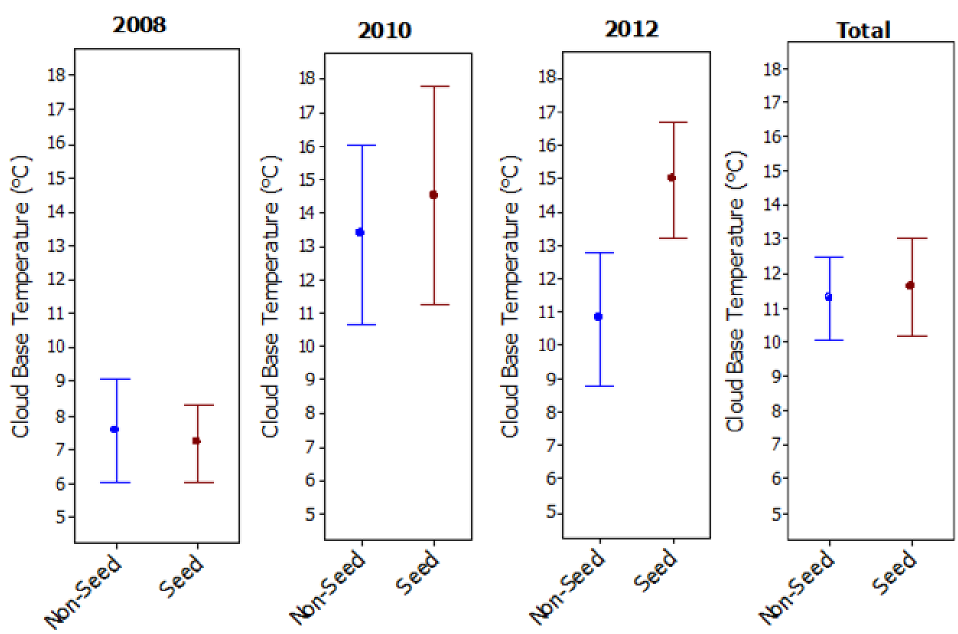


Figure 14: North Dakota measurements of cloud base temperature for each POLCAST project (2008, 2010, and 2012), and three years combined. The bars (above and below) represent one standard deviation of the mean. Red represents seed cases and blue represents non-seed cases.

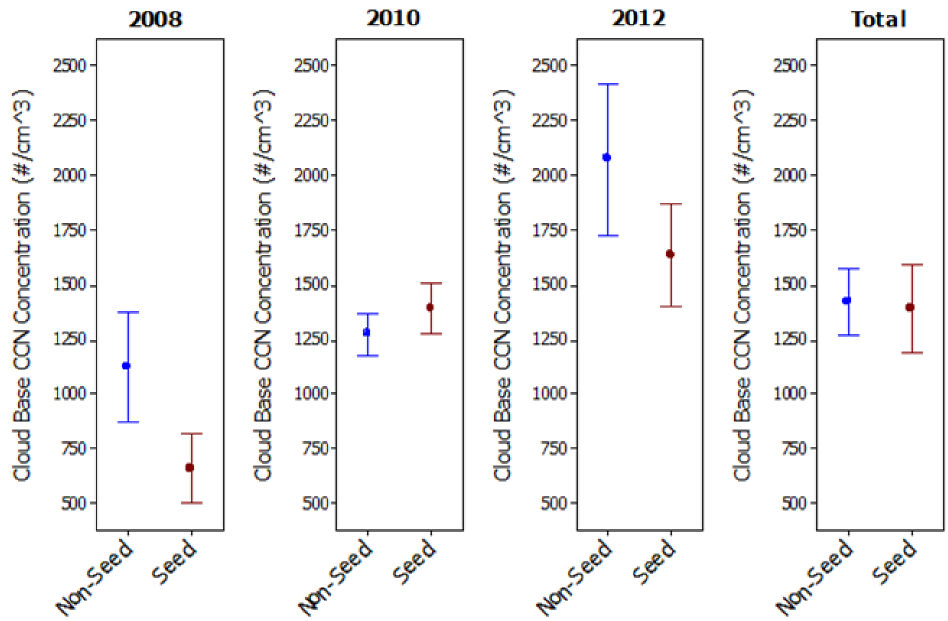


Figure 15: North Dakota measurements of cloud base Cloud Condensation Nuclei (CCN) concentration for each POLCAST project (2008, 2010, and 2012), and three years combined. The bars (above and below) represent one standard deviation of the mean. Red represents seed cases and blue represents non-seed cases.

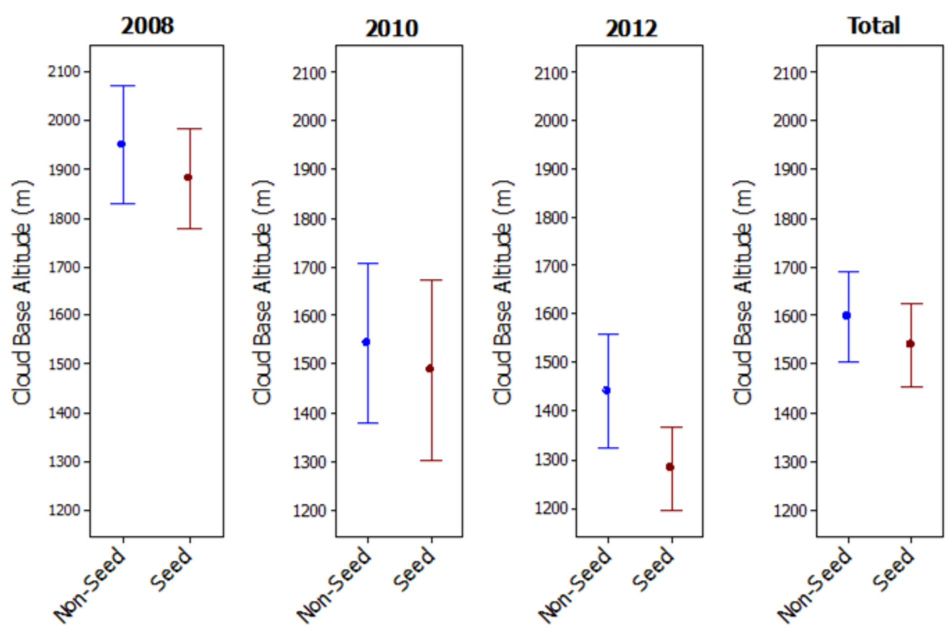


Figure 16: North Dakota measurements of cloud base altitude for each POLCAST project (2008, 2010, and 2012), and all three years combined. The bars (above and below) represent one standard deviation of the mean. Red represents seed cases and blue represents non-seed cases.

Figure 17, Figure 18, and Figure 19 show box and whisker plots of cloud base CCN, pressure altitude, and temperature for each date of a flight during POLCAST, giving a distribution of the measurements of environmental factors for seeded and non-seeded cases. Generally, the plots are very similar indicating similar distributions for each project and between the seeded and non-seeded cases.

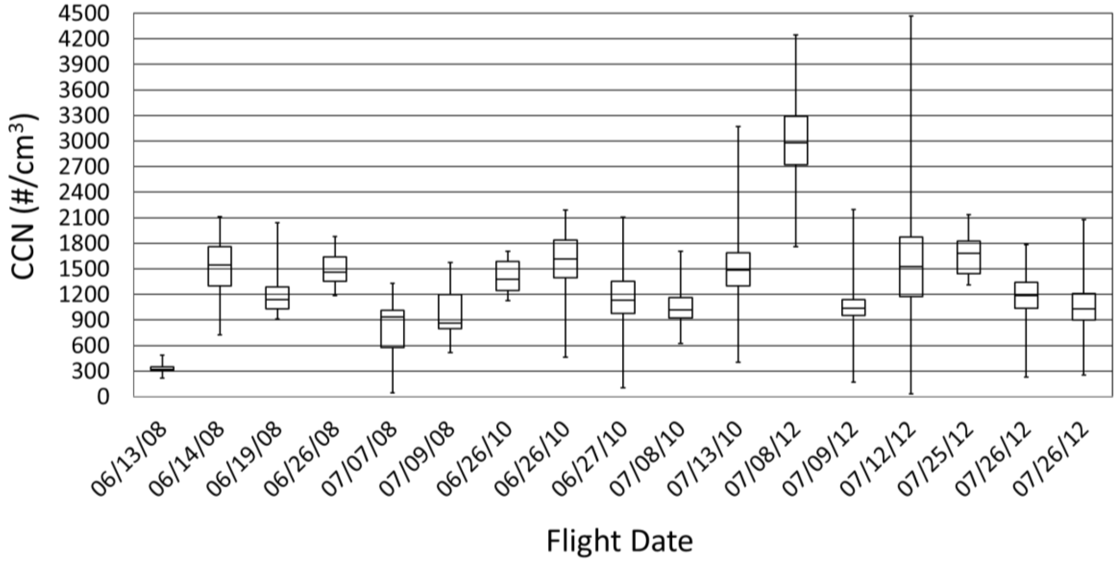


Figure 17: Statistical distributions of Cloud Condensation Nuclei Concentration measured by the UWyo CCN counter at 0.6 % ambient supersaturation at cloud base during summers of 2008, 2010, and 2012 in North Dakota.

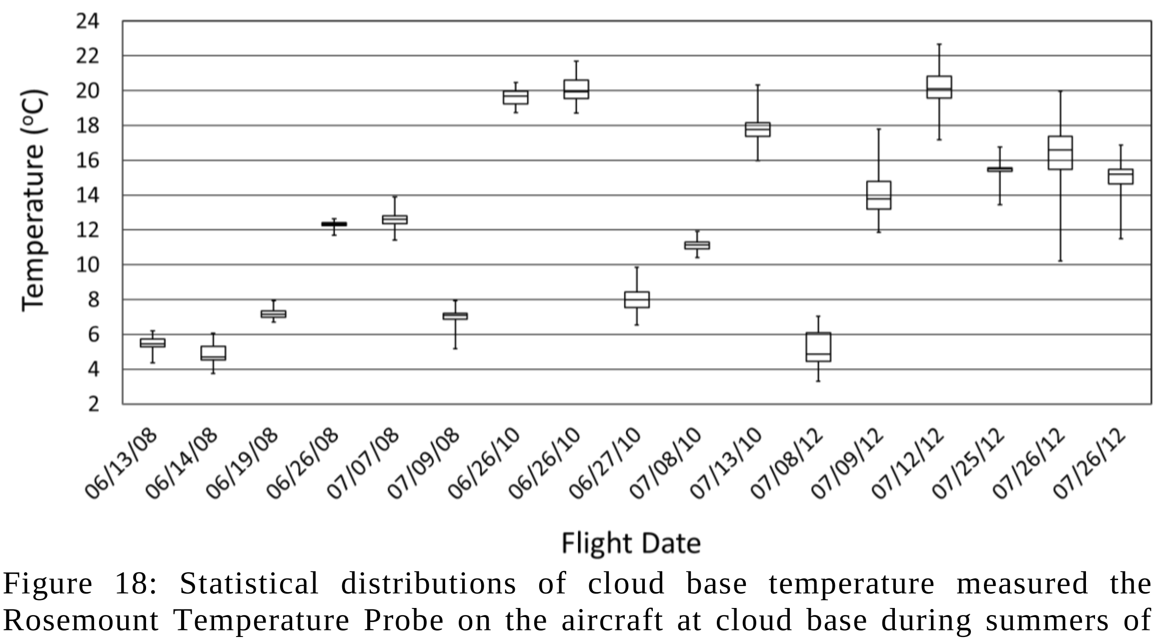


Figure 18: Statistical distributions of cloud base temperature measured the Rosemount Temperature Probe on the aircraft at cloud base during summers of 2008, 2010, and 2012 in North Dakota.

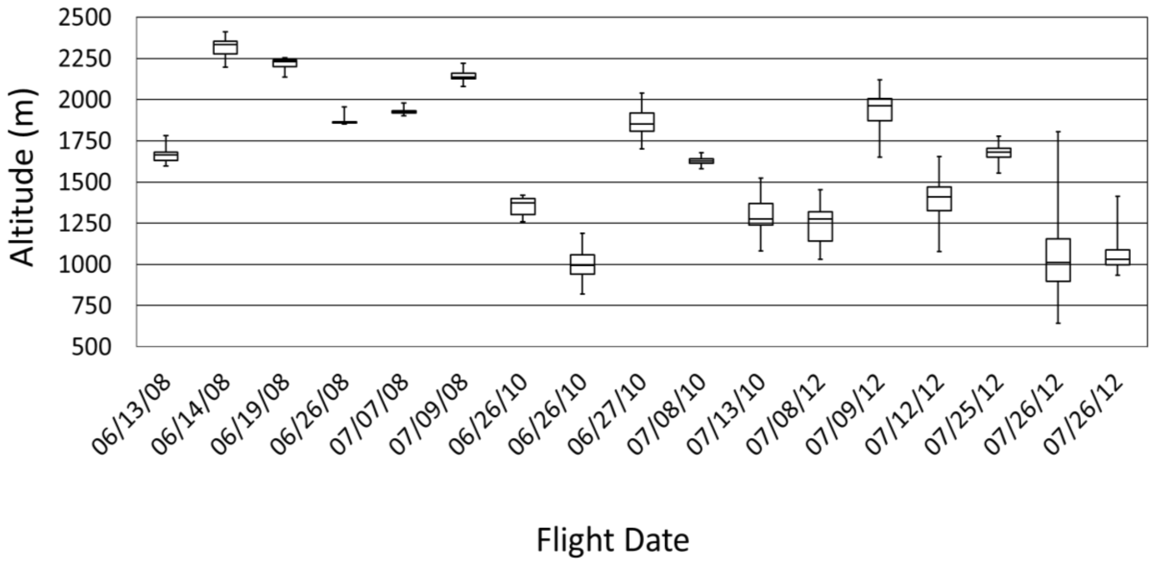


Figure 19: Statistical distributions of cloud base altitude measured by the pressure transducer on the aircraft at cloud base during summers of 2008, 2010, and 2012 in North Dakota.

MANN-WHITNEY

The Mann-Whitney statistical test is applied to data from each year of the POLCAST project individually as well the combined 2008, 2010, and 2012 POLCAST data set. Table 4 shows the Mann-Whitney results and significance (p-value) for the environmental factors from the 37 cases and Table 5 shows the single ratio for each environmental factor. A ratio value close to one shows similarity of measurements taken of clouds seeded compared to non-seeded clouds.

Table 4: List showing the Mann-Whitney statistic and associated p-values for the environmental factors (cloud condensation nuclei (CCN) concentration, temperature, and altitude). The values for the combined years of 2008, 2010, and 2012 are shown in addition to each POLCAST project separately.

	Mann-Whitney U				P-Value			
	Combined	2008	2010	2012	Combined	2008	2010	2012
CCN	154.5	9.0	5.0	33.50	0.620	0.180	0.571	0.815
Temperature	153.5	15.0	7.0	22.50	0.599	0.699	1.00	0.20
Altitude	158.5	15.0	6.0	34.5	0.707	0.699	0.786	0.888

Table 5: Single ratio values of seeded cases compared to non-seeded cases for the environmental measured during POLCAST field projects (2008,2010, and 2012).

Environmental Factor	Single Ratio
Cloud Base CCN Concentration	0.982
Cloud Base Temperature	1.026
Cloud Base Altitude	0.963

Of the 37 cases included in the environmental factor analysis, four cases could not be included in radar analysis. Storms not lasting past the first 10-minute scan or showing an echo on radar are not included in TITAN analysis, resulting in 33 cases to be included in the rainfall analysis. Cases removed include one seed case and three non-seed cases; resulting in 17 seed cases and 16 non-seed cases analyzed Table 6 shows the percentage of clouds still present at 10-minute time periods up to 60 minutes past seeding or sampling, showing seeded clouds lived longer than non-seeded clouds. Similar results were seen in projects conducted in South Africa and Mexico, where the longer lasting storms were not necessarily a result of seeding, but of naturally occurring dynamic effects. The average rain rate for the 33 cases (Figure 21 and Figure 22) shows seeded storms lasted longer and had higher rain rates than non-seeded storms. Increase in the rain rate and increase in the rain amount (Figure 20) are positive indications of seeding influence. Statistical analysis was done by applying the Mann-Whitney to the double ratio (last 40 minutes/first 20 minutes) of seeded and non-seeded 33 original cases. The result of the Mann Whitney test was a significance of 0.063.

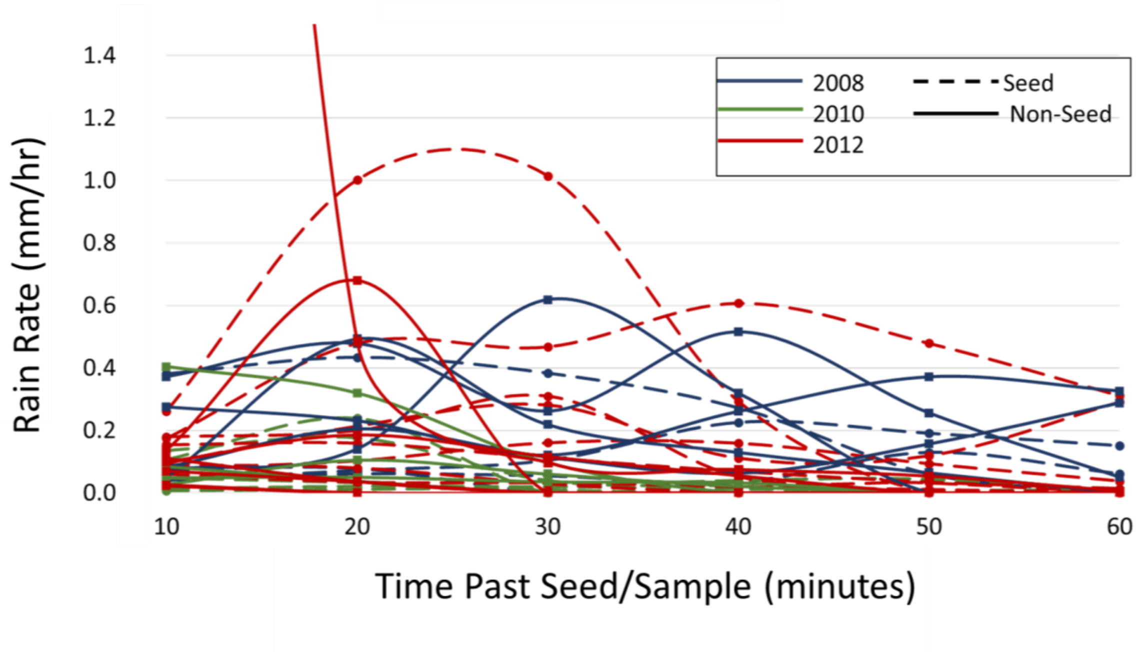


Figure 20: Plot showing the rain rate for 33 POLCAST cases up to 60 minutes past seeding/sampling. The cases from 2008 are in blue, 2010 cases are in green, and 2012 cases are in red.

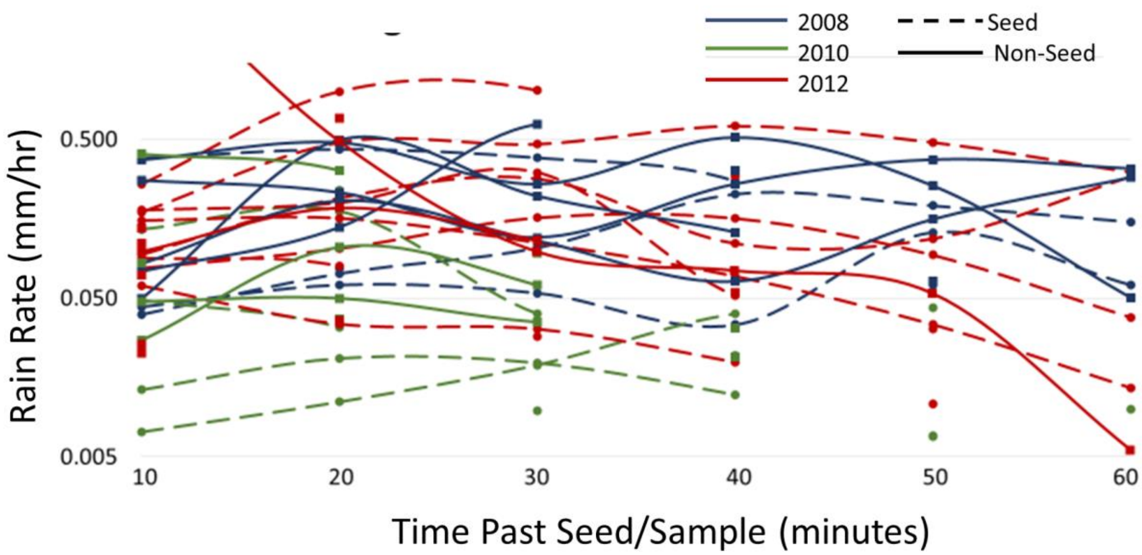


Figure 21: Log plot of the rain rate for the POLCAST data set up to 60 minutes past seeding/sampling. The cases from 2008 are in blue, 2010 cases are in green, and 2012 cases are in red.

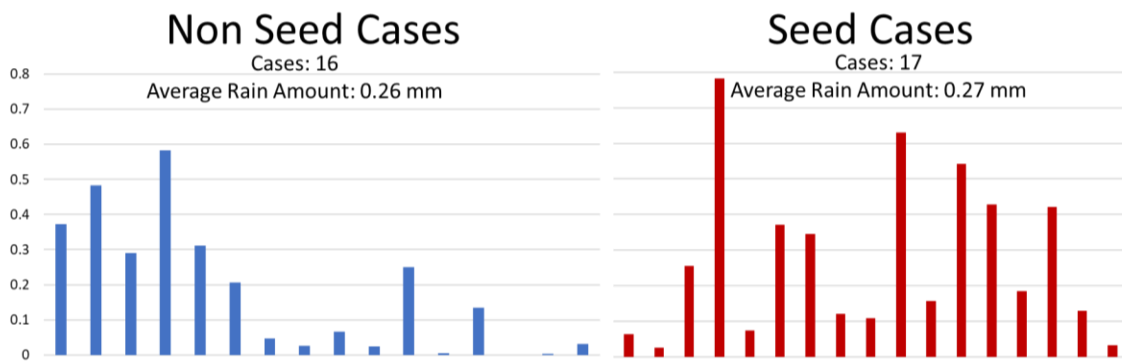


Figure 22: The average rain amount (mm) for each case during the three years of POLCAST. The non-seed cases are in blue and seed cases in red.

Table 6: Showing the percentage of seeded and non-seeded cases that had a radar echo at 10-minute periods past seeding or sampling from 20 minutes to 60 minutes.

	>20 min	> 30 min	> 40 min	> 50 min	> 60+ min
Seeded Cases	100 %	88 %	82 %	76 %	41 %
Non-seeded Cases	88 %	62 %	56 %	31 %	25 %
Percent Difference	13 %	35 %	38 %	84 %	49 %

BOOTSTRAP AND STATISTICS

Bootstrapping is done on two separate data sets: 33 cases from radar analysis for three field projects and 15 cases from the 2012 field project. For the 33 cases, bootstrapping creates 100, 1,000, and 10,000 new data sets of 66 cases, 132 cases, and 264 cases. One hundred data sets of 30, 60, and 120 cases were created from the POLCAST4 data set. The double ratio test is applied to the 30 to 60-minute/10 to 20-minute time check rain amounts for each data set, and the average is calculated. Ratios greater than 1.0 indicate that seeding had an impact on convective clouds in North Dakota, as seen in Table 7. Therefore, the ratio of seeded to non-seed increases for each 10-minute period, showing a positive seeding influence. A larger ratio was calculated for 30 – 60 minutes past the end of seeding due to the result of non-seeded clouds not lasting as long as the seeded clouds. Table 9 and Table 10 show results for data sets created from the POLCAST2, 3, and 4 data set and POLCAST4.

Table 7: Single ratios for the 10-minute time periods up to 60 minutes after seeding or sampling finished for the 33 cases of the rain amount (mm).

Time after seeding/sampling	Seed Total Rain Amount/ Non-Seed Total Rain Amount	Seed Avg Amount/ Non-Seed Avg Rain Amount
10 minutes	1.25	1.818
20 minutes	2.30	1.894
30 minutes	3.16	2.112
40 minutes	3.21	2.220
50 minutes	3.47	1.446
60 minutes	2.77	1.585

Table 8: Values of average reflectivity and calculated single ratio of seed/non-seed.

Reflectivity (dBZ)			
Time Past	Seed (Average)	Non-Seed (Average)	SR = Seed Avg/ Non-Seed Avg
10 minutes	15.048	10.990	1.369
20 minutes	17.042	13.464	1.266
30 minutes	15.932	12.241	1.302
40 minutes	10.541	10.541	1.444
50 minutes	12.571	12.751	1.000
60 minutes	14.238	11.440	1.245

Table 9: Average Probability values calculated from the Mann-Whitney test applied to the double ratios of the radar derived rain rate for seed/non-seed of two time periods, the last 40 minutes/first 20 minutes.

	66 Cases			**132 Cases**			**264 Cases**		
Iterations	10^2	10^3	10^4	10^2	10^3	10^4	10^2	10^3	10^4
P-value	0.03	0.03	0.03	0.003	0.004	0.004	0.00004	0.00008	0.00005
Average Double Ratio	1.98	2.00	1.96	1.94	1.92	1.94	1.92	1.92	1.92

Table 10: Average probability values calculated from the Mann-Whitney test applied to the double ratios of the radar derived rain rate for seed/non-seed of two time periods, the last 40 minutes/first 20 minutes.

	30 Cases			**60 Cases**			**120 Cases**		
Iterations	10^2	10^3	10^4	10^2	10^3	10^4	10^2	10^3	10^4
P-value	0.20	0.17	0.18	0.14	0.13	0.14	0.06	0.08	0.08
Average Double Ratio	2.27	2.35	2.36	2.25	2.31	2.31	2.31	2.27	2.29

NDAWN STATION DATA

Precipitation data is included from North Dakota Atmospheric Weather Network (NDAWN) stations within 100 km of the UND radar. The locations and the years of data for all NDAWN stations within the POLCAST area are shown in Table 11, with stations used in analysis in bold text. Locations included in analysis have archived precipitation data from the 1990's to present, which is an indication of the climatology of measured rainfall of the area. Knowledge of precipitation received at NDAWN locations within the POLCAST study area is helpful to determine if 2008, 2010, and 2012 are 'typical' or 'atypical' precipitation years. The total rain rate for the months of June and July for the Grand Forks station are shown in Figure 24 with boxes around 2008, 2010, and 2012, showing that the years POLCAST took place are typical of what is seen in the area. Plots for the other stations are included in Appendix A.

Table 11: North Dakota Agriculture Weather Network stations within 120 km of the University of North Dakota Radar. The latitude, longitude, elevation, and approximate distance away from the UND radar are included. Stations with bolded text are ones which are included in analysis.

Station Name	Latitude	Longitude	Elevation (ft.)	Distance	Years of Data
UND Radar	47.922	-97.086	932	NA	NA
Ada, MN	47.321	-96.514	910	80 km	2007 – 2016
Cavalier, ND	**48.762**	**-97.755**	**988**	**106 km**	**1994 – 2016**
Eldred, MN	**47.688**	**-96.822**	**861**	**32 km**	**1995 – 2016**
Forest River, ND	**48.296**	**-97.603**	**893**	**56 km**	**1992 – 2016**
Grafton, ND	48.412	-97.186	801	55 km	2006 – 2016
Grand Forks, ND	**47.836**	**-97.067**	**846**	**10 km**	**1990 – 2016**
Inkster, ND	48.166	-97.710	1149	53 km	2009 – 2016
Mavie, MN	48.121	-95.971	1168	86 km	2002 – 2016
Mayville, ND	**47.498**	**-97.262**	**952**	**49 km**	**1995 - 2016**
McHenry, ND	47.685	-98.623	1676	117 km	1995 – 2016
Michigan, ND	48.019	-98.172	1521	82 km	2003 – 2016
Perley, MN	**47.179**	**-96.680**	**895**	**88 km**	**1995 – 2016**
St.Thomas, ND	**48.601**	**-97.493**	**865**	**83 km**	**1994 – 2016**
Stephen, MN	48.457	-96.854	1072	62 km	1994 – 2016
Warren, MN	48.137	-96.839	854	30 km	1995 – 2016

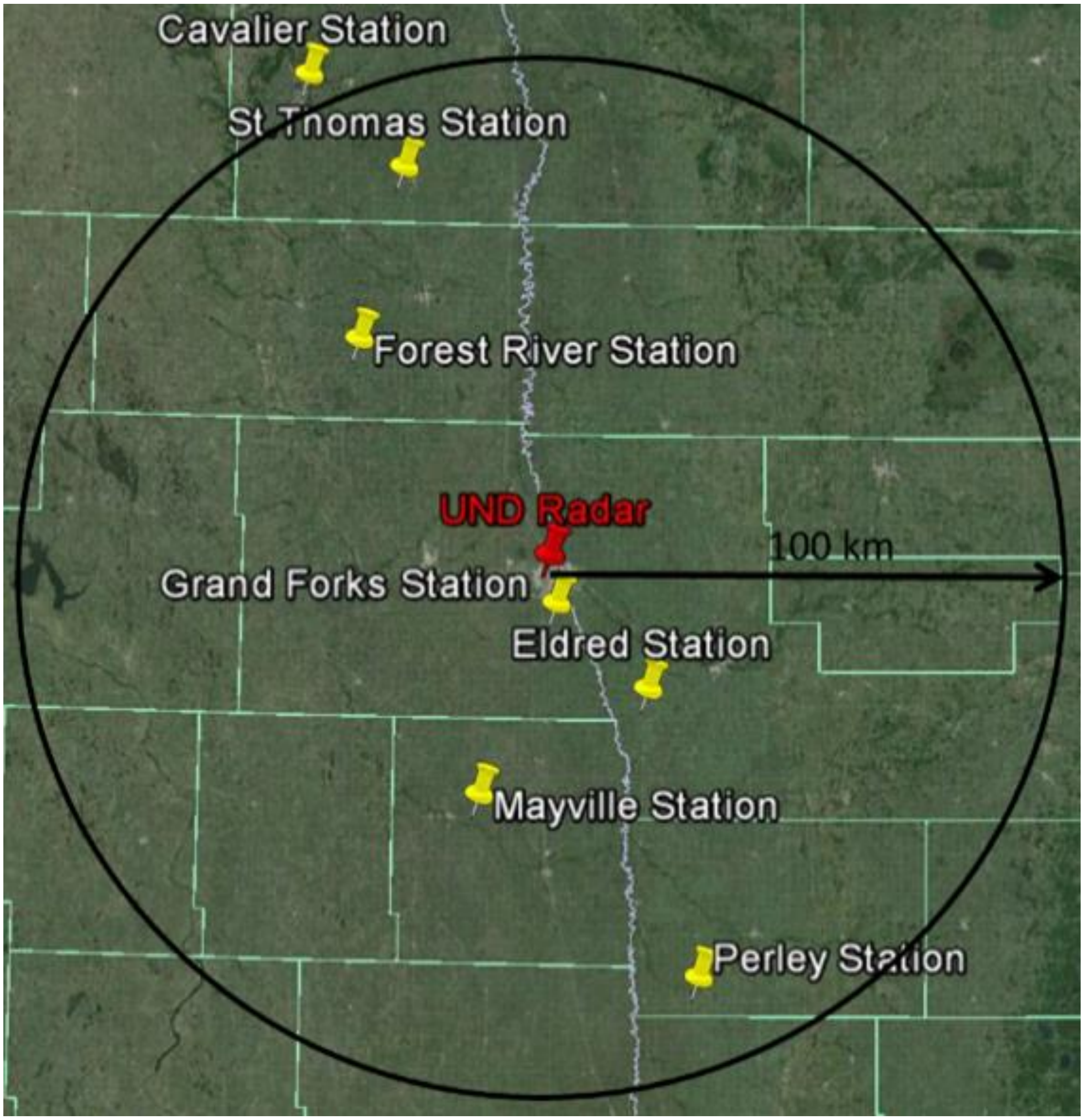


Figure 23: Map showing a 100-kilometer radius (black circle) of the University of North Dakota (UND) along with North Dakota Agriculture Weather Network locations (yellow pins) within 100 km, and the UND Radar (red pin).

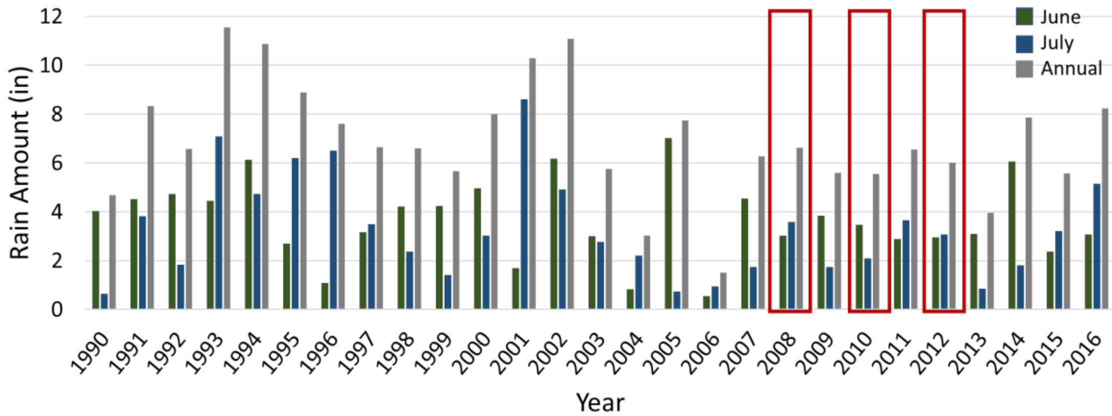


Figure 24: Rainfall amounts measured at the Grand Forks, North Dakota NDAWN station from 1990 to 2016. The red boxes are around the years POLCAST took place (2008, 2010, 2012).

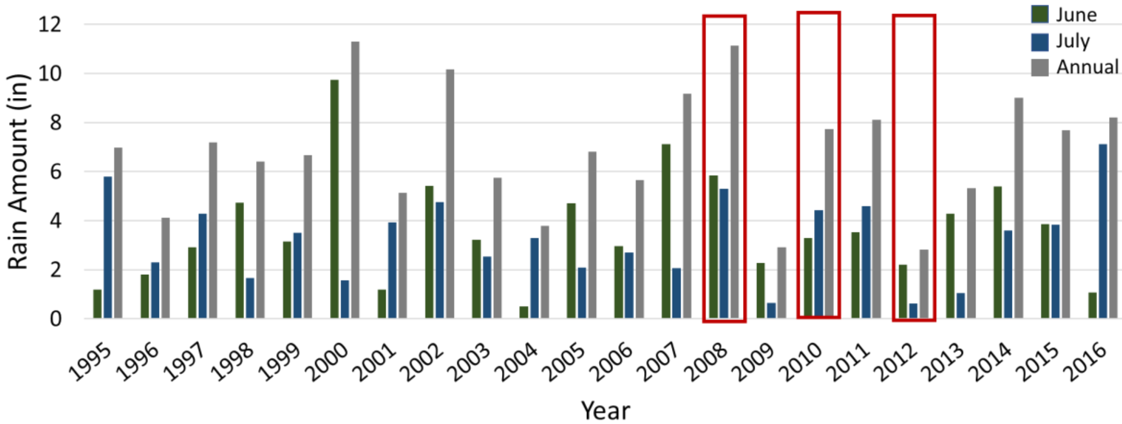


Figure 25: Rainfall amounts measured at the Perley, Minnesota NDAWN station from 1995 to 2016. The red boxes are around the years POLCAST took place (2008, 2010, 2012).

CHAPTER VII

CONCLUSION AND FUTURE WORK

A total of 44 cases collected during the POLCAST projects in 2008, 2010, and 2012: 37 cases were analyzed based on environmental factors and 33 analyzed based on radar return. Seed and non-seed cases from the three-year project appear to be homogeneous with respect to cloud base environmental factors (cloud condensation nuclei concentration, temperature, and altitude). With homogeneous clouds between the seeded and non-seeded cases, effects of hygroscopic particles released into the updraft can be determined without worrying the effects are due to differences in these environmental factors. Clouds are tracked with radar up to 60 minutes with 41 % of seeded clouds and 29 % of non-seeded clouds lasted 60 minutes past the completion of seeding/sampling. With a positive effect of increased lifetimes for clouds seeded, rainfall has a greater probability to last longer and be more wide spread. The longer lasting clouds may be a result of the dynamic effects taking over and not from the effects of the hygroscopic particles.

The Mann-Whitney statistical test and ratio statistics applied to the rain amount and environmental factors give a representation of cloud microphysics in North Dakota as well as an indication of effects of hygroscopic seeding on precipitation enhancement in North Dakota. The rain amount, derived and calculated from radar reflectivity, results in a single ratio of 1.56, which is a 56 % increase in the average rain amount received during seeded cases. To account for variability, the double ratio statistic is applied to the data set of seed and non-seed case; rain amount during the last 40 minutes compared to the rain amount during the first 20 minutes. Results of the double ratio statistic on the original 33 cases resulted in a p-value of 0.063. Positive results are shown in the double ratio and single ratio statistics, indicating seeding is efficient in enhancing the precipitation formation in clouds. Even though the data set of 33 cases does show a positive increase in the clouds chosen as cases, more cases are required to accurately represent the effect of seeding.

Bootstrapping is done on the rain amount of the 33 cases to create new data sets that indicate the number of cases for statistical significance to be calculated, based on the three years of POLCAST data. Unlike some conceptual models of hygroscopic seeding, the clouds seeded with flares during POLCAST did not increase the precipitation rate, but did indicate a positive effect on radar derived rain rate. The seeding effect would only be a small percentage and not outside the 'typical' precipitation received in the area. NDAWN stations located within the POLCAST study area show that precipitation during June and July of 2008, 2010, and 2012 is not unusual. Results from the three randomized POLCAST projects show a positive influence of hygroscopic flares in North Dakota clouds.

The original data set consisting of 33 cases, though not statistically significant, allowed for an indication of the influence that hygroscopic particles have on the radar return and radar derived rain rate in seeded clouds compared to non-seeded in Eastern North Dakota. Seeded clouds during POLCAST showed an increase in lifetime and rain amount compared to non-seeded clouds. In order to implement hygroscopic seeding as operational in North Dakota, a field project including at least 17 more cases would be required to increase the data set to approximately 50 cases calculate statistical significance.

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APPENDIX A

There are seven North Dakota Atmospheric Weather Network (NDAWN) stations located within the POLCAST study area; two in Minnesota and five in North Dakota. The rainfall data for June and July are provided for each station from the 1990's to 2016. POLCAST took place during June and July of 2008, 2010, and 2012 and analysis of the rainfall data is used to show that the years chosen for the project are not unusual in rainfall amount. The plots of the NDAWN stations indicate that June and July of the POLCAST years are typical of the area. The Grand Forks and Perley stations are shown above and the station data from Cavalier, Eldred, Forest River, Mayville, and St. Thomas are shown in Figure 26 to Figure 30.

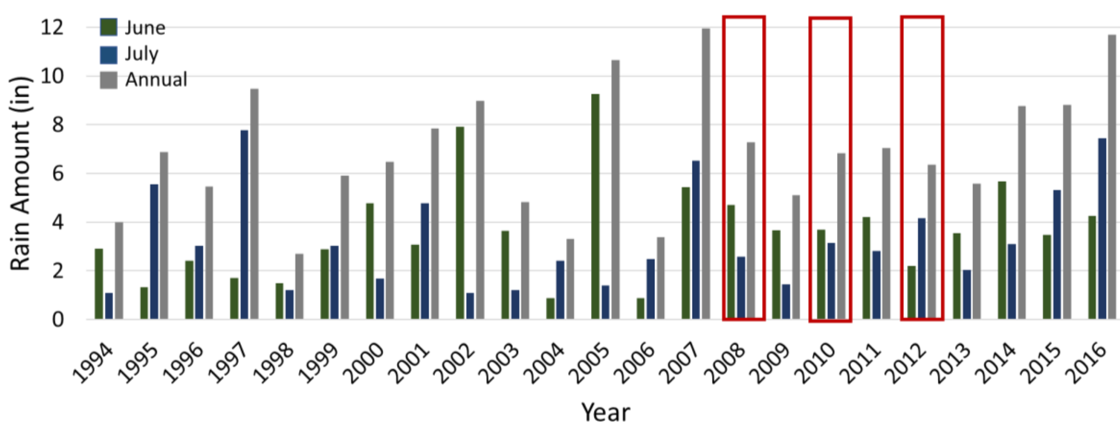

Figure 26: Rainfall amount measured at the Cavalier NDAWN station from 1994 to 2016. The black boxes are around the years POLCAST took place (2008, 2010, 2012).

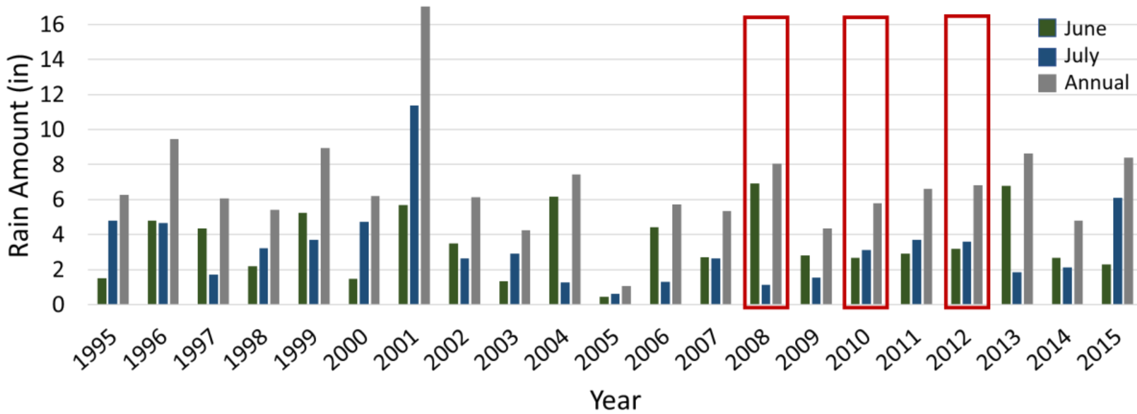

Figure 27: Rainfall amount measured at the Eldred NDAWN station from 1995 to 2016. The red boxes are around the years POLCAST took place (2008, 2010, 2012).

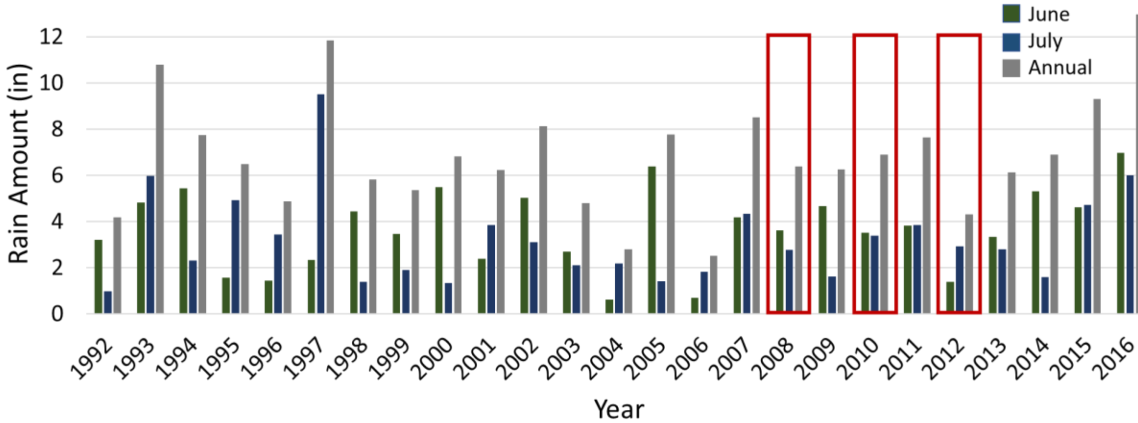

Figure 28: Rainfall amount measured at the Forest River NDAWN station from 1992 to 2016. The red boxes are around the years POLCAST took place (2008, 2010, 2012).

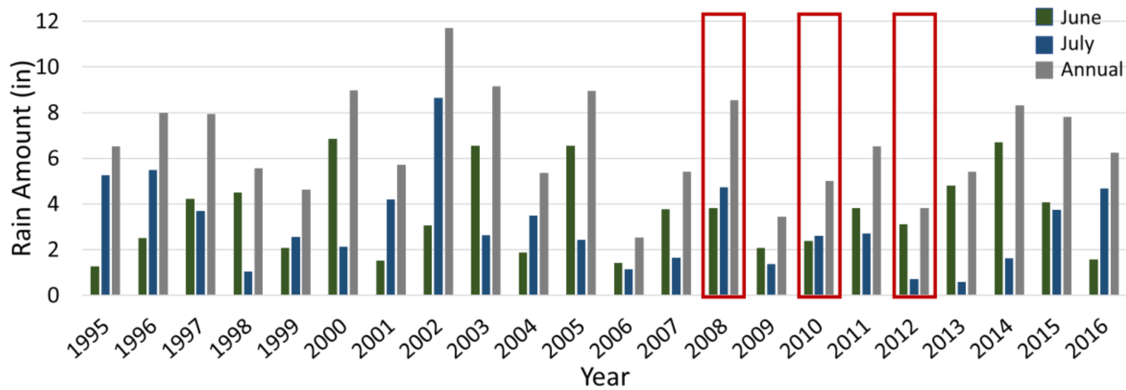

Figure 29: Rainfall amount measured at the Mayville NDAWN station from 1995 to 2016. The red boxes are around the years POLCAST took place (2008, 2010, 2012).

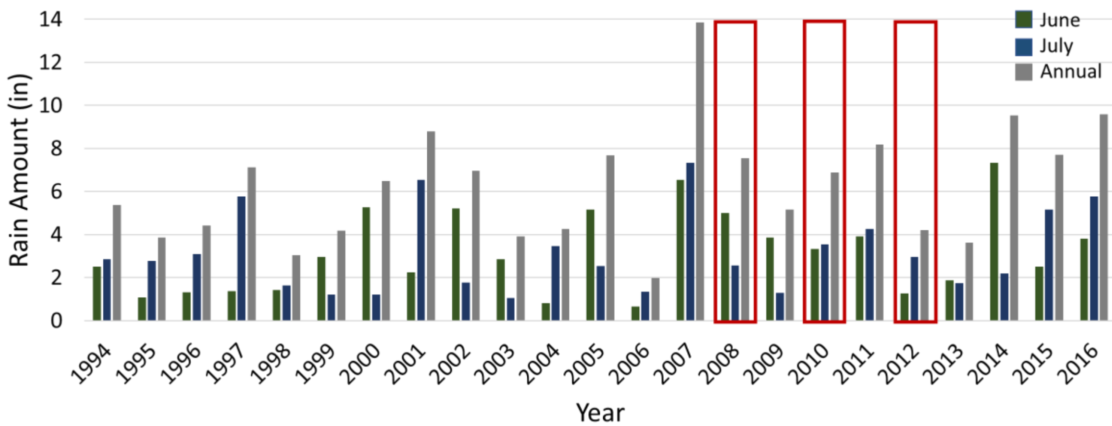

Figure 30: Rainfall amount measured at the St. Thomas NDAWN station from 1994 to 2016. The red boxes are around the years POLCAST took place (2008, 2010, 2012).

APPENDIX B

```
#!/usr/bin/env python
#
# NAME:
#   Ratio_RainAmt_POLCAST.py
#
# PURPOSE:
#   To perform a bootstrapping statistical test on the data collected during all
#   POLCAST projects to create 100 data sets of a specified number of data.
#   These data sets can then be used for other statistical tests.
#
#
# Define what will be imported to run the code
import pandas as pd
import numpy as np
import os, zipfile, glob, re, sys

from pandas import read_csv
import shutil
import csv
import scipy
import math
from scipy import stats
from scipy.stats import mannwhitneyu

# Define the .csv files that can be injested into the script.
Input_files = pd.Series(['POLCASTRainAmt_Rat'])
List_of_Samples = range(0,101)

# Define the number of samples for the files to have.
num_of_values = pd.Series([66,132,264,528])
TimeSteps = pd.Series([10,20,30,40,50,60])
np.seterr(divide='ignore')

# Make directories to move files to based on the number of cases.
for file in Input_files:
   dir = 'nas/home/jekness/Bootstrap_POLCAST/ResampledFiles/file'
   if os.path.exists(file):
      shutil.rmtree(file)
   os.mkdir (file)
   os.chdir (file)

# Read in each of the files.
   df = pd.read_csv('/Nas/home/jekness/Bootstrap_POLCAST/%s.csv' %(file))
   for i in List_of_Samples:

# Create data sets of size n for each of the files to later have more statistical tests applied.
      for n in num_of_values:
         Data = df.ix[np.random.random_integers(0, len(df)-1, n)]
```

```
# Separate the data set into variables to use in calculations.
            Resampled = Data.fillna(0)
            SeedvsNon= Resampled.groupby('Case')
            SeedCases = SeedvsNon.get_group('Seed')
            NonSeedCases = SeedvsNon.get_group('Non')
            S_N_Sum = SeedvsNon.sum()
            S_N_AVG = SeedvsNon.mean()
            Seed10_20 = (S_N_Sum['Sum10_20'][0])
            Non10_20 = (S_N_Sum['Sum10_20'][1])
            Seed30_60 =(S_N_Sum['Sum30_60'][0])
            Non30_60 =(S_N_Sum['Sum30_60'][1])
            SeedRat = SeedCases.T[3:4]
            Seed_Ratio  = SeedRat.T
            NonRat = NonSeedCases.T[3:4]
            Non_Ratio = NonRat.T
            RatAVGSeed=(S_N_AVG['Ratio'][0])
            RatAVGNon = (S_N_AVG['Ratio'][1])
            RatSeed_RatNon = RatAVGSeed/RatAVGNon
            Seed60_Seed10 = Seed30_60/Seed10_20
            Non60_Non10 = Non30_60/Non10_20
            Ratios = (RatAVGSeed,RatAVGNon,RatSeed_RatNon)
            All = (SeedCases,NonSeedCases)
            MW_Non = (Seed60_Seed10, Non60_Non10)
            MannWTest = mannwhitneyu(Seed_Ratio,Non_Ratio)
            with open('Ratio_%stimes.csv' %(n), 'a') as f:
                writer = csv.writer(f)
                writer.writerow(Ratios)
            with open('MannWTest_%stimes.csv' %(n), 'a') as f:
                writer = csv.writer(f)
                writer.writerow(MannWTest)

# Write data to csv files.
            with open('SeedOVERNon_%s.csv' %(n),'a') as f:
                writer = csv.writer(f)
                writer.writerow([Seed60_Seed10, Non60_Non10])
            my = read_csv('SeedOVERNon_%s.csv' %(n))
            my.columns = ['Seed60_10','Non60_10']
            my.to_csv('Seed_NonSeed_%s.csv' %(n))
            with open('AllData_S_N_%s_%s.csv' %(n,i),'a') as f:
                writer = csv.writer(f)
                writer.writerow([All])
os.chdir ('..')
```

APPENDIX C

The University of North Dakota radar located on the roof of Clifford Hall, NorthPOL, was used during each of the POLCAST projects. NorthPOL is a C-band radar which operates with a 5.4 cm wavelength and 5,600 MHz frequency. With a wavelength of ~5 cm, droplets important to the collision and coalescence process return a signal to the radar. The C-Band pulse volume of 150-200 km range is one cubic km (Wikipedia 2013); therefore, short range observations are preferred (WeatherEdge 2017). The POLCAST study area was a 150 km radius from the radar and within the detection range for a C-band radar (Saara 2014) and limit attenuation, the weakening of the energy by either being absorbed or scattered as it encounters dust or hygrometers downstream of the radar (Haby 2014). C-band radars like NorthPOL have dual polarization capability (Figure 25) which allows the C-band to have the similar performance to an S-band radar (Saara 2014) when detecting precipitation sized particles. Higher cost, longer wavelength (10.7 cm), smaller frequency (2,800 MHz), and inability to perform sector scans are reasons the NWS S-band radar was not used for the POLCAST projects. Standard scan time for S-Band, such as those used by the National Weather Service, can scan to look at 14 different elevations every 5 minutes during severe weather (NWS 1999). In clear air mode, the S-band radar can scan 5 different elevation angles in 10 minutes. S band radar are more sensitive to precipitation sized particles (~2 mm) while the C band radar that has a shorter wavelength can detect cloud droplets resulting from the collision and coalescence process, prior to the droplets becoming rain drops (Atmo336 2001).

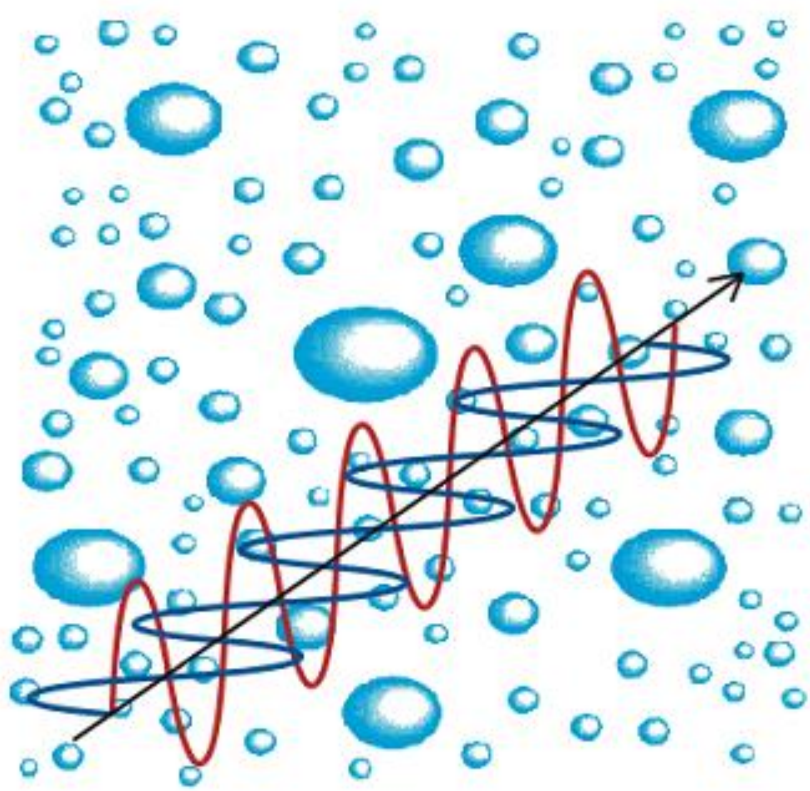

Figure 31: Image showing dual polarization of a radar beam; the red shows the vertical oscillation and blue the horizontal oscillations. The black arrow represents the direction of propagation. (Saara 2014)

A C-band radar was useful during POLCAST and could be implemented in future projects. A Ka-band radar could also be a beneficial addition in future seeding projects. The Ka-band radar operates at a frequency of approximately one cm (Matrosov et al. 1999) and is primarily used to look at drizzle drops and fog and would be mounted on the wing of an aircraft during a future project. Having the Ka-Band radar on the aircraft would collect data of small droplets within the cloud or light/moderate rainfall and could be used during a seeding event to track smaller changes than would be seen by a C-band radar. A significant percentage of total precipitation comes from light precipitation events with a rain rate less than 15 mm/h (Mazin, 1989); therefore, using a radar with a shorter wavelength would be beneficial. Smaller drops could then be observed and more of the precipitation process tracked by using two radars, one C-Band and 1 Ka band, for future projects.