Suitability of North Dakota for Conducting Effective Hygroscopic Seeding

David J. Delene

Department of Atmospheric Sciences, University of North Dakota,
Grand Forks, North Dakota, United States of America

Abstract. One goal of the Polarimetric Cloud Analysis and Seeding Test (POLCAST) project is to determine if North Dakota clouds created by surface-base convection are suitable for treatment with hygroscopic flares to enhance surface rainfall. The evaluation of suitability uses field measurements to examine processes involved in the hygroscopic seeding conceptual model to determine if the North Dakota environment is conducive to effective seeding. POLCAST field measurements are used to determine if the environment supports hygroscopic seeding as a means to increase precipitation. Current scientific theories and modeling results indicate that the most important environmental factors are cloud condensation nuclei (CCN) concentrations, droplet size distribution, and cloud base temperature and height. Cloud modeling indicates that North Dakota's high CCN concentration supports increases in precipitation efficiency from releasing large hygroscopic particles at cloud base. North Dakota's cloud base temperatures and cloud depths indicate that ice phase hydrometeors are important in the precipitation process. Hence, net increases in precipitation efficiency do not depend on just the warm rain process, but also involve graupel production in the cold-cloud region. Given North Dakota's low cloud base heights, increases in precipitation should increase rain at the surface. The environmental factors examined indicate that North Dakota is suitable for precipitation enhancement through hygroscopic seeding. However, some cloud processes are impossible to fully evaluate with the current POLCAST data set. A more complete aerosol/cloud physics data set would further our understanding of the physical processes involved and facilitate the development of a more accurate regional precipitation forecast model. Development, validation, and use of a precipitation forecast model with a known uncertainty would provide an effective method for quantifying precipitation changes resulting from hygroscopic seeding.

1. INTRODUCTION

North Dakota has a long weather modification history which includes a commitment to conducting research (Stith 1983), development of evaluation methods (Miller et al. 1983), and using the latest technology (Boe and Jung 1990; Schneider and Langerud 2011). North Dakota cloud seeding started in the 1950s with ground-based silver iodide activities with the primary goal to augment precipitation. In 1961 hail suppression activities began (Miller and Fuhs 1987). Since the 1960s, airborne platforms have been the preferred method of delivering seeding material (Langerud and Moen 1998). North Dakota sponsored research in the 1960s and 1970s to investigate reducing hail damage and increasing rainfall (Boyd et al. 1976; Rose and Jameson 1986). The State created the North Dakota Weather Modification Board in 1975. A state managed cost-sharing program, North Dakota Cloud Modification Project (NDCMP), started in 1976 (Smith et al. 1992). In 1981, the Weather Modification Board became part of the State Water Commission. Legislation in 1987 changed the Board's name to the Atmospheric Resource Board. On August 1, 1995, the

Atmospheric Resource Board became an official division of the State Water Commission with responsibility for administering cloud seeding activities in the state, conducting weather modification research and development, and collecting weather-related data.

Over half the annual losses to North Dakota's small grain crops are from hail damage and drought (Rose and Jameson 1986) which has a significant impact on the State's economy (Bangsund and Leistritz 2009). Hence, when research results indicated that hygroscopic cloud seeding can enhance precipitation (Bruintjes 1999) there was interest in knowing if North Dakota was suitable for the technique. Therefore, the North Dakota Atmospheric Resource Board started the Polarimetric Cloud Analysis and Seeding Test (POLCAST) research program in 2006, to determine effectiveness of hygroscopic cloud seeding in North Dakota. While hygroscopic cloud seeding in South Africa, Mexico City and Thailand (Mather et al. 1997; Terblanche 2005) had positive statistical results, it is important to determine if North Dakota is similarly conducive before implementing such operations. Furthermore, these new statistically-positive results did not fully account for potential multiplicity in the analyses (Silverman 2003), so the POLCAST program included a randomized seeding experiment. Multiplicity is due to conducting more than one statistical test on an experimental data set which results in a *p-value* being less reliable than many scientists assume (Nuzzo 2014). The goal of this paper is not to present a statistical evaluation, but rather a physical evaluation using airborne measurements to determine if North Dakota is suitable for effective hygroscopic seeding.

Convective clouds only transform approximately 10 percent of ingested water vapor into precipitation that reaches the Earth's surface (Langhans et al. 2015). The low precipitation efficiency of such clouds has prompted scientists to propose enhancement of water supplies by means of cloud seeding with hygroscopic material (Czys and Bruintjes 1994). Fresh water supplies would increase if clouds converted more water vapor into precipitation. Laboratory, modeling, and observational studies have demonstrated that aerosols can modify the micro-structure of cumulus clouds (e.g., Levin and Cotton 2008). The physical processes are similar whether pollution modifies cloud micro-structure inadvertently to produce an undesirable outcome or seeding material deliberately changes cloud micro-structure to promote a desired outcome, such as precipitation enhancement. As argued by some scientists (Garstang et al. 2005), it seems logical to use the same definition for scientific proof since physical processes are the same when using aerosols for weather modification and when pollution aerosols effect clouds. However, the National Research Council concludes that there is not yet statistical nor physical evidence required to establish weather modification's scientific validity (Garstang 2003). Irrespective of the definition of scientific proof, the larger amount of scientific research related to inadvertent weather modification and anthropogenic climate change is relevant to the conceptual model of hygroscopic seeding.

Cloud seeding involves deliberately modifying cloud properties by introducing seeding material, such as silver iodide, dry ice, liquid carbon dioxide, or hygroscopic aerosols. Cloud modification projects have preferred using silver iodide as the seeding material for the past 60 years since AgI has no environmentally harmful effects (Williams and Denhom 2009) and is an ice nucleus that can effectively modify cloud micro-structure. The atmosphere typically lacks naturally occurring ice nuclei because only a small fraction of aerosols nucleate ice formation (DeMott et al. 2011). Hence, there are often areas of supercooled liquid water in developing clouds where introducing more ice nuclei converts small liquid cloud droplets into larger ice particles, which promotes precipitation development (Lohmann and Feichter 2005). While glaciogenic seeding using ice nuclei may be promising for precipitation enhancement in “cold” clouds, hygroscopic seeding has advantages because the seeding material can affect “warm” clouds, those that never grow cold enough to produce ice.

The paper's goals are to further understanding of processes involved in the conceptual model of hygroscopic seeding and to document the POLCAST research on North Dakota convective clouds. Hygroscopic seeding suitability is determined using analysis of POLCAST aircraft measurements. In particular, cloud modeling results are combined with calculated statistical distribution of cloud base CCN, cloud base temperature, cloud base height and cloud microphysical measurements to determine if seeded clouds are likely to produce more precipitation than natural clouds. The POLCAST observations are discussed in terms of processes within the chain of events, from seeding to rain falling on the ground. Details are provided on instrument deployment, measurement techniques, and analysis tools so results are understandable and reproducible. Significant details on software tools utilized in these analyses are provided so that readers may use the tools in their own work. While including software information lengthens the article, such details are necessary to enable reproducibility of results, which is fundamental to the scientific method. As scientists learn that some important results cannot be reproduced, research standards are increasing (Begley and Ellis 2012), which means projects require more care and papers greater detail.

1.1 Conceptual Model

Conceptual models incorporate the best scientific understanding and link the chain of events that move the process from cause to effect. A conceptual model should be an “effective theory” (Randall 2011) that incorporates what is important at different scales and uses the precision and accuracy of instruments to determine if observations support the theoretical model. While theoretical models can be based on what turns out to be an incorrect understanding, the conceptual model should incorporate the best current science. If some parts of the model are incorrect, then new observations combined with “skeptical empiricism” (carefully thought-out and tested research) will disprove aspects, and the conceptual model will be revised. A provisional conceptual model is not a hindrance to scientific progress but an essential element since it provides statements which researchers may disprove. The lack of a well-defined conceptual framework dooms a technique to remain un-supported, scientifically. However, a well-defined conceptual model provides a pathway for a technique to be scientifically proven. Scientists can focus on single aspects of each process, rather than trying to address the complete process all at once. This divide-and-prove methodology allows for collaboration among researchers whereby different teams focus on different parts of the overall process. Furthermore, it allows research conducted for other purposes (e.g. climate change) to be used to validate weather modification techniques.

Our hygroscopic seeding concept for increasing precipitation from summer North Dakota convective clouds produced by surface heating has the following chain of events. 1.) Burning hygroscopic flares (Mather et al. 1997) produces air containing larger diameter cloud condensation nuclei (CCN) than what naturally occurs in the environment. 2.) Updrafts loft the air containing seeding material into the base of clouds. 3.) Above the cloud base, the growth process of water vapor condensing on larger CCN produces a broader cloud droplet spectrum which results in more collector droplets. 4.) The coalescence process produces larger drops as the collector droplets coalesce with smaller droplets. 5.) The ice phase process results in more graupel (by number and mass) due to higher concentrations of larger drops, which harvest more of the available supercooled water before the air parcel reaches cloud top; thereby, increasing the precipitation efficiency of the cloud. 6.) The increase in cloud precipitation efficiency results in more rain at the surface. Cloud micro-structure changes may also increase surface water by initiating rain earlier and/or prolonging the life of a cloud by strengthening the coupling of the updraft–downdraft storm propagation mechanism.

Previous research studies support the steps in our conceptual model's chain of events. The first item in the chain of events is burning the hygroscopic flares to generate particles. POLCAST employs Ice Crystal Engineering (ICE) burn-in-place hygroscopic flares, which improves over South Africa flares by burning at a higher temperature. Recent research indicates that ICE hygroscopic flares generate more particles above 0.4 µm than the South Africa flares and the larger particles are a result of aggregation of KCl and $Ca(Cl)_2$ (Bruintjes et al. 2012). Furthermore, parcel model (Cooper et al. 1997) simulations show that the ICE flares produce larger drops at shorter cloud lifetimes than the South Africa flares. Pilot estimates and Aircraft Integrated Meteorological Measurements System (AIMMS) probe measurements below developing North Dakota convective clouds show mean updrafts in the range of 0.6 to 1.4 m/s (120 to 275 ft/min) (Simelane et al. 2013). Therefore, clouds ingest material produced by burning hygroscopic flares on sub-cloud base aircraft. Observation of hygroscopic seeding on cloud properties is challenging because it is difficult to know when seeding has affected the cloud volume being sampled. However, model simulations showed that seeding with hygroscopic flares could increase rainfall amounts in continental clouds having 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 (Yin et al. 2000).

1.2 POLCAST Overview

The POLCAST field projects are cooperative experiments funded by the North Dakota Atmospheric Resource Board (NDARB). Ice Crystal Engineering, LLC, (ICE) provides the hygroscopic burn-in-place cloud seeding flares (Ice Crystal Engineering 2016), which are manufactured to the same specification throughout all the POLCAST field projects. Weather Modification, Inc. (WMI) provides the seeding aircraft and majority of research instruments. The University of North Dakota (UND) and the National Center for Atmospheric Research conduct analysis of the POLCAST data set. The POLCAST field projects include five components: 1.) measurements using the UND C-band polarimetric Doppler weather radar, 2.) cloud seeding and airborne measurements using a Cessna 340 aircraft, 3.) in situ cloud microphysical sampling using the instrumented UND Citation Research Aircraft, 4.) surface aerosol measurements in Grand Forks, North Dakota, and 5.) special Weather Research and Forecasting (WRF) model runs for the project area. Not all the components are part of each field project. The focus of this paper is airborne measurements conducted in 2008, 2010, and 2012. Other publications cover other components of the POLCAST project.

During the summer of 2006 (10 July – 5 August), the Polarimetric Cloud Analysis and Seeding Test (POLCAST2006) field program investigated the detectability of hygroscopic seeding by polarimetric radar observed or by derived radar fields. Analysis of POLCAST2006 polarimetric derived liquid water content (LWC), rainfall rates, and hydrometeor type for seeded and non-seeded convective systems indicated that polarimetric radar could detect the hygroscopic seeding effect; however, with only eight seeded cases the data set is far too small to produce statistically significant results (Kucera et al. 2008). The results from POLCAST2006 indicated that average radar-derived LWC increased after hygroscopic seeding. One POLCAST2006 case did not show an increase in LWC; however, it was located along the edge of a larger, more stratiform area of precipitation. The rainfall rate analysis indicated positive results, with an increase in average maximum rainfall rate and rain duration. The hydrometeor identification program produced results in agreement with ZDR and reflectivity trends; however, there is considerable uncertainty in hydrometeor identification retrievals without proper verification of the algorithm. No airborne flight measurements are available from POLCAST2006.

From 9 June through 11 July 2008, a second field program (POLCAST2008) expanded on POLCAST2006 with inclusion of airborne measurements. During the summer of 2010 (21 June – 23 July), a third field program (POLCAST2010) added airborne measurements from the Citation Research Aircraft (Delene and Poellot 2015). During the summer of 2012 (27 July – 3 August), a fourth field program (POLCAST2012) conducted airborne measurements with the seeding aircraft, and deployed two Droplet Measurement Technologies (DMT) CCN counters and two UWyo CCN counters.

To improve operations, POLCAST2010 included setup and operation of the Weather Research and Forecasting (WRF) model (Mullendore and Starzec 2016). WRF forecasts and radar observations agree well with the ten cases analyzed during June and July 2010, the number of cells of 30 dBZ or greater reflectivity (stratified by cell size) predicted by WRF and observed by radar were generally within 2-3 cells (Starzec 2014). Furthermore, comparison of total number of cells (> 5 dBZ) predicted and observed from the entire project showed matching frequency for the largest cells (greater than 900 km^2), under-forecasting of the smallest cells (less than 45 km^2) and a slight over-forecasting of mid-range cell bins. Additionally, forecast results were also compared to observations by percent areal coverage, instead of cell count; this alternative verification showed that in cases where both model and observations showed any convection, most cases matched areal coverage within 5%.

2. AIRCRAFT MEASUREMENTS

POLCAST2008 consists of twelve flights (24.83 hours) between 10 June and 11 July 2008 with 11 flights conducting in-situ measurements (Figure 1). A 50/50 treatment randomization (seed or no-seed) of target candidates ensured a balanced statistical comparison. The criteria for POLCAST seeding candidates are that the cloud is relatively isolated from surrounding convection, and initial development is within 100 km of the UND radar. Furthermore, the candidate needs to be located within North Dakota, have at least 2.5 m s^{-1} (500 ft min^{-1}) cloud base updraft (pilot estimated) and the cloud base temperature has to be warmer than 4 °C. The 2.5 m s^{-1} (500 ft min^{-1}) updraft requirement is an estimate of the maximum updraft and cloud with continuous updrafts in the 1.0 - 2.5 m s^{-1} (200-500 ft min^{-1}) range for several seconds are seeded. Radar analysis of six cases using the Thunderstorm Identification, Tracking, Analysis, and Nowcasting (TITAN, Dixon and Weiner 1993) software indicated that the methodology of using polarimetric radar data to analyze "areas of influence" is a promising seeding effect evaluation technique (Delene et al. 2011). Additionally, airborne measurements show that the cloud base aerosol and droplet concentrations are generally relatively high during summer in North Dakota with Passive Cavity Aerosol Spectrometer Probe (PCASP) aerosol concentrations of 890 cm^{-3}, CCN concentrations (May 2008 calibration) of 1,030 cm^{-3}, and cloud droplet concentrations of 360 cm^{-3}.

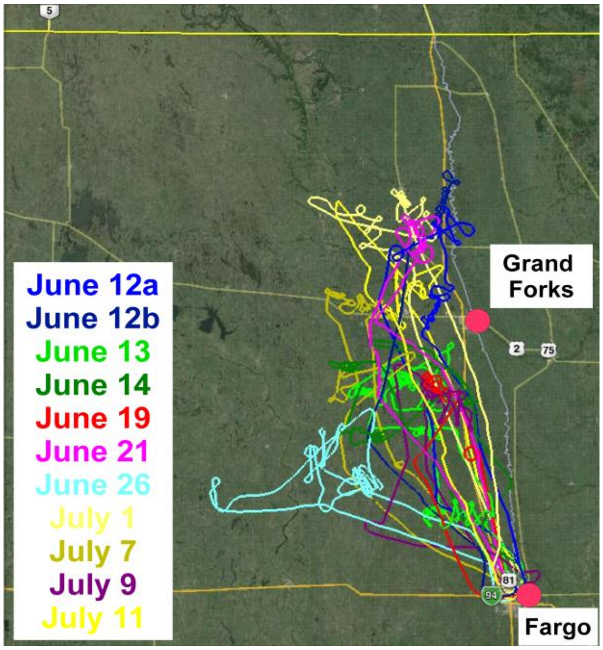

Figure 1: Image showing seeding aircraft tracks for 2008 research flights. Each track color corresponds to the color of the legend flight date. The white line between the cities of Fargo and Grand Forks (red dots), and extending into Canada, is the Red River of the North, the boundary between North Dakota and Minnesota. The solid yellow line near the top is the Canadian border and the other (narrower) yellow lines are major highways. Image is created using Google Earth software to display Keyhole Markup Language files that contain the aircraft's GPS position.

POLCAST2010 consists of 11 seeding flights (26.2 hours) between 23 June and 20 July 2010. Clouds base measurements are conducted by the seeding aircraft and the

Citation Research Aircraft (N555DS) made cloud microphysical measurements (Figure 2). The six flights (7.6 hours) by the Citation Research Aircraft allow measurements of the onset of coalescence while enabling the seeding aircraft to focus on treatment of cloud targets. Keeping the seeding aircraft at cloud base provides more cases for the randomized seeding experiment, which is a POLCAST priority. POLCAST2010 uses the same randomized seeding method as POLCAST2008 and has thirteen hygroscopic seeding targets.

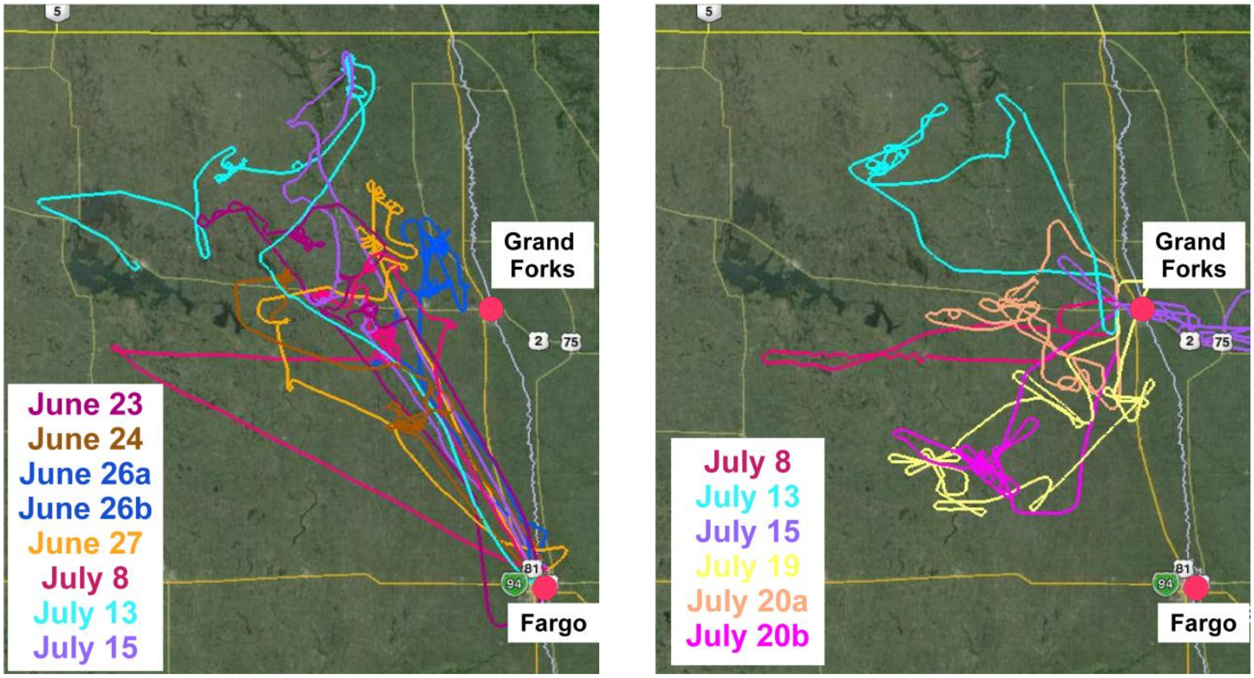

Figure 2: Images showing seeding aircraft (left) and Citation Research Aircraft tracks (right for 2010 research flights. Each track color corresponds to the legend date. The white line between the cities of Fargo and Grand Forks (red dots) and extending into Canada, is the boundary between North Dakota and Minnesota. The solid yellow line near the top is the Canadian border and other (less broad) yellow lines are major highways. Images created using Google Earth software to display Keyhole Markup Language files that contain the aircraft's GPS position.

POLCAST2012 consists of eleven aircraft flights (20.7 hours) between 2 July 2012 and 29 July 2012 but no Citation Research Aircraft flights (Figure 3). POLCAST2012 has fifteen hygroscopic seeding targets and uses the same randomized seeding method as in 2008 and 2010. The 2012 campaign continued where 2010 left off with the same randomized sequence. POLCAST2012 has an Aventech Aircraft-Integrated Meteorological Measurement System (AIMMS) probe to measure the cloud base updraft velocity. Also, for POLCAST2012, two CCN counters are operated on the seeding aircraft and two CCN counters are operated together on the surface to test for any systematic differences in measurements that may result from the counters employing different measurement techniques. The focus is on airborne measurements conducted during all POLCAST field projects; therefore, analysis of the DMT CCN counter's airborne measurements is beyond the paper's scope.

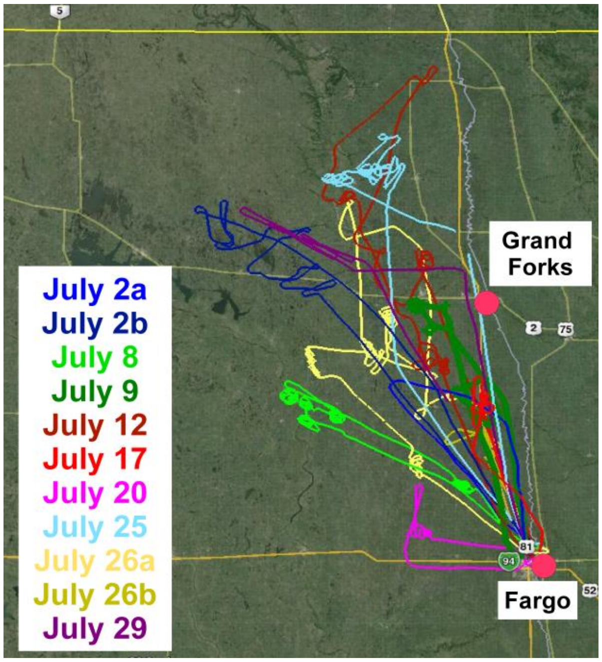

Figure 3: Image of seeding aircraft tracks for 2012 research flights. Each track is color corresponds to the legend flight date. The white line between Fargo and Grand Forks and extending into Canada, is the boundary between North Dakota and Minnesota. The solid yellow line near the top is the Canadian border and the lighter yellow lines are major highways. Image is created using Google Earth software to display Keyhole Markup Language that contain the aircraft's GPS position.

2.1 Airborne Measurements

The POLCAST field projects used a Cessna 340 aircraft (registration number N98585) for cloud base seeding and in-situ measurements. The WMI facility in Fargo, North Dakota is the base of the Cessna 340 aircraft which meant the flight scientist based at the operations center in Grand Forks would have to drive to Fargo on possible flight days. The POLCAST operations center is the Clifford Hall radar control room on the UND campus. POLCAST conducts flights only during daylight with typical take-off times between 1-4 pm local time. The aircraft is configurable (Figure 4) for deployment of the following equipment.

- **Droplet Measurement Technology (DMT) Cloud Condensation Nuclei (CCN) Counter -** Measures the number concentration of aerosols that activate to form cloud droplets at supersaturations between 0.1 and 1.0 percent.
- **University of Wyoming (UWyo) Cloud Condensation Nuclei (CCN) Counter** - Measures the number concentration of aerosols that activate to form cloud droplets at supersaturation between 0.3 and 1.6 percent.
- **PMS Passive Cavity Aerosol Spectrometer Probe with SPP100 Electronics (PCASP SPP200)** - Measures the particle size spectrum between 0.1 and 3.0 µm in diameter.
- **Forward Scattering Spectrometer Probe with SPP100 Electronics (FSSP SPP100)** - Measures cloud droplets between approximately 3.0 and 47.0 µm in diameter.
- **Aventech Aircraft-Integrated Meteorological Measurement System (AIMMS)** - Measures 3-dimensional winds.
- **Rosemount Aircraft Temperature Sensor** - Measures total air temperature.

- **Edgetech Dew Point Sensor** - Measures dew point temperature.
- **Aircraft GPS System** - Measures position and aircraft ground speed.
- **Science Engineering Associates (SEA) M300 Data System** - Acquires, displays and records data from all aircraft research instrumentation.
- **Cloud Seeding Pyrotechnic Racks** - Carries up to 24 one-kilogram hygroscopic flares.

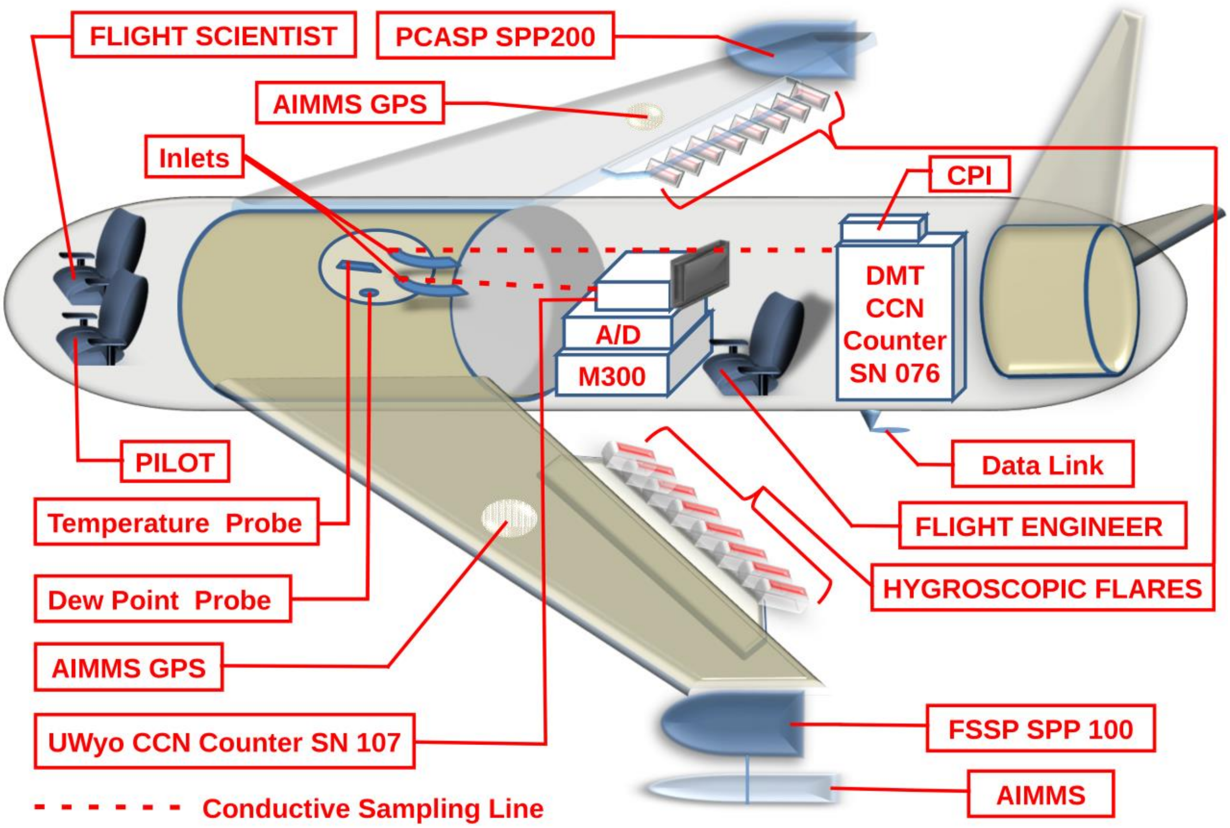

Figure 4: Diagram of the Cessna 340 aircraft configuration for 2012. The 2010 and 2008 aircraft configurations are similar except the Droplet Measurement Technologies (DMT) cloud condensation nuclei (CCN) counter and aircraft integrated meteorological measurements system (AIMMS) probe are not on the aircraft in 2010. A DMT constant pressure inlet (CPI) system maintains the DMT CCN counter at a constant pressure of 700 hPa. Flexible conductive tubing of 6.35 mm (0.25 inch) diameter connects the reverse facing inlets to the CCN counters and two additional ports (not shown) provide the exit for the air sample. An analog-to-digital board (A/D) records voltage outputs from the University of Wyoming (UWyo) CCN counter, the dew point probe, and temperature probe. Data are downloaded in real-time using a 465 MHz data radio. The bullet list of instruments defines all acronyms. Image created using LibreOffice software.

Since the Cessna 340 aircraft requires only a single pilot, a flight scientist occupies the right front seat. The flight scientist is responsible for ensuring that the flight's scientific objectives are achieved. The POLCAST flights are flown by two experienced WMI pilots, either Hans Ahlness or Jody Fisher. Either Cedric "Tony" Grainger and David Delene is the flight scientist, and a UND student researcher is the flight engineer. The flight engineer follows a check list for instrument start-up and shutdown, and is responsible for operating the M300 data acquisition system and monitoring instrumentation for indications of any problems.

The Citation Research Aircraft is configured to carry the following instruments (Figure 5).

- **Droplet Measurement Technologies (DMT) Cloud Droplet Probe (CDP)** - Measures cloud droplets between approximately 3 and 50 µm diameter in 30 sized channels while providing particle-by-particle information on the first 256 droplets detected in a sampling interval.
- **King Hot Wire Liquid Water Content Probe (LWCP)** - Measures cloud liquid water content.
- **2-Dimensional Cloud Imaging Probe (2D-C)** - Measures the number concentration and 2-dimensional shape of cloud droplets.
- **SPEC High Volume Precipitation Spectrometer (HVPS)** - Measures the number concentration and 2-dimensional shape of precipitation sized particles.
- **EdgeTech Digital Aircraft Hygrometer (Dew Point Temp.)** - Measures ambient dew point temperature.
- **Rosemount Aircraft Temperature Sensors (Temp. Probe)** - Measures ambient air temperature when combined with an air speed measurement.
- **Applanix Corporation Position and Orientation System for Airborne Vehicles** – Provides 3-dimensional atmospheric winds when measurements are combined with the Nose Boom Gust Probe measurements.
- **Pitot Tubes with Pressure Transducers (Pitot Tube)** - Measures the aircraft speed relative to the ambient air.
- **Aircraft GPS System** - Measures position and aircraft's ground speed.
- **Sulfur Hexafluoride (SF_6) Analyzer** - Detects trace amounts of SF_6 released from the seeding aircraft.
- **Data Radio** – Uses 465 MHz frequency to receive real-time position information from the seeding aircraft.
- **Science Engineering Associates (SEA) M300 Data System** - Acquires, displays and records data from aircraft research instrumentation.

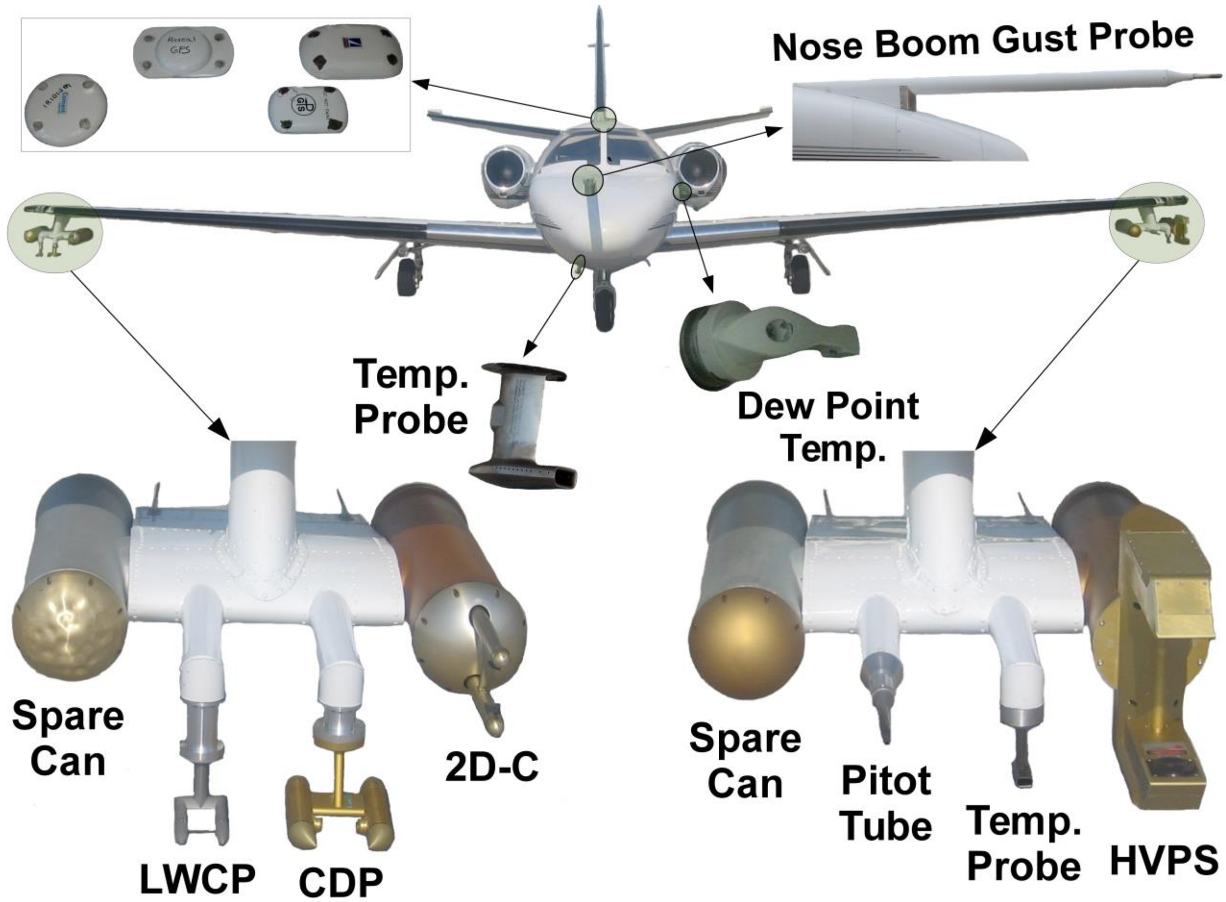

Figure 5: Diagram of the Citation Research Aircraft as configured for 2010, the only year of project participation. An analog-to-digital board (A/D) records voltage outputs from the dew point temperature sensor and temperature probe. Acronyms are defined in the bullet list of instruments. Image is created using LibreOffice and GNU Image Manipulation Program (GIMP) software.

The Citation Research Aircraft requires two pilots to meet insurance requirements. The flight scientist, David Delene for POLCAST2010, sits centrally, just aft of the pilots. The forward cabin position allows a clear view of flight environment, enables easy interaction with the pilots and allows instrument monitoring through the M300 data acquisition system. Two seats are available for flight engineers who follow a check list to start up and shut down equipment and monitor instruments for problems throughout the flight. The M300 data acquisition system on the Citation Research Aircraft obtains and displays the Cessna 340 seeding aircraft position in real-time using a 465 MHz data link. The flight crew uses a dedicated “science” radio frequency for communication with the seeding aircraft and the POLCAST control center.

2.2 Data Processing

The Science Engineering Associates (SEA) model 300 data acquisition system (M300) acquires all data at a minimum sampling frequency of at least 1 Hz. The open-source Airborne Data Processing and Analysis software package (ADPAA) post-processes the M300 binary file by creating individual instrument files, processes the data using the concept of data levels and creates a summary data file for each flight (Delene 2011). The summary data file contains all parameters necessary to conduct scientific analysis. ADPAA is able to handle all model M300 and model M200 SEA data acquisition system files. ADPAA includes calibration information to correctly process data from all UND Citation Research Aircraft projects since 2000 and many research projects conducted by WMI in addition to POLCAST. ADPAA is not limited to airborne applications but also processes POLCAST surface (Cochran et al. 2013) and laboratory data. The author has even processed data from rockets and unmanned aircraft system platforms using ADPAA (Tilley et al. 2011).

All ADPAA files are freely available from the SourceForge subversion repository (Delene et al. 2016) and an archive available at Zenodo (Delene 2016a). Therefore, it is not necessary to describe processing equations here, and the interested reader is referred to the ADPAA software itself. The software fully documents how a single module (group of files organized into a directory) processes data from an instrument. Typically, a single file within a module contains the data processing methodology with other files providing data input and output functionality. The level of input data that a module uses provides the top-level organization (i.e. Level 1, Level 2, Level 3, or Level 4) to ADPAA's instrument modules. The ADPAA tree (SourceForge Wiki) is available on the Web so particular instrument modules and processing files can easily be located. Obtaining some scientifically important parameters, such as air temperature, requires modules from different levels which can make it difficult to follow the data flow. Hence, the SourceForge ADPAA wiki (SourceForge Wiki) provides documentation on data flow for important parameters in the "Instrument Processing Streams" section. The wiki defines modules used to derive an important parameter but does not provide step-by-step processing instructions since details are available within the modules themselves.

POLCAST data is automatically processed on Linux servers by using ADPAA code within the "scripts" module. A wiki page (SourceForge Wiki) provides details on ADPAA hierarchical structure of scripts. ADPAA's top-level script, *process_all_dir*, calls POLCAST field project level scripts: *process_all_polcast2*, *process_all_polcast3*, and *process_all-polcast4*. We have re-processed all M300 raw files using the same code version (9 December 2015) to create our analysis data set. The processing date is contained in the meta-data of all files and the SourceForge repository enables extraction of code on a particular day. Therefore, reproducibility of our results is enhanced by having the software openly available since the data set can be regenerated and the code used to create the data set will always be accessible (Ince et al. 2012).

2.3 Data Quality Control

Data quality control involves obtaining an instrument's calibration, conducting periodic checks to ensure expected instrument performance, and ensuring measurements are representative of the ambient environment (Delene 2011). Some instruments (e.g. total temperature probes) cannot easily be coupled to the environment so measurements are adjusted to ambient conditions. POLCAST personnel performed weekly quality control procedures on all aircraft instruments. The flight scientist ensures the FSSP and PCASP are sizing correctly by challenging the instrument with standard-sized beads. The flight scientists ensure the CCN counter is not contaminated by challenging the system with an inlet particle filter. Additionally, a hand-held vacuum pump is used to measure the system's leak rate, which must be low for deployments on pressurized aircraft (Delene and Sever 2009). As found during one POLCAST2008 flight, leaks can result in measuring significantly lower CCN concentrations than what are actually in the environment (Delene et al. 2011). Though the on-board flight scientist and flight engineers monitor measurements continuously, aircraft flights can be busy so instrument problems can be missed. Since data processing is automated, flight measurements are reviewed by project personnel shortly after each flight. While the ADPAA Cplot2 program (Delene 2016b) generates “quick-look” plots, POLCAST data is reviewed interactively using Cplot2, which allows for re-plotting and examination of all available data.

POLCAST found that CCN counters require more robust quality control procedures and calibrations than most other airborne instruments. The field projects use serial number 107 UWyo CCN counter (Delene et al. 1998) for cloud base measurements. POLCAST operates the UWyo CCN counter at a single supersaturation to obtain sufficient samples for accurate average measurements within the time interval (approximately 12 minutes) that seeding material is released into clouds. The UWyo CCN counter requires approximately 30 s to obtain a sample when operated at a single supersaturation; therefore, sampling under a single cloud would provide approximately 24 samples. Occasionally, the CCN counter would sample material from seeding flares. Seeding material is only encountered away from clouds where updrafts are not present to move the material upward before the next aircraft pass. The quality assurance procedure removes flare aerosol measurements from the analysis data set. When cloud targets are not seeded as part of the randomized experiment, the aircraft still samples under cloud base for 12 minutes to mark the area of influence for use in radar cell analysis (Delene et al. 2011).

Calibration of the UWyo CCN counter uses a condensation particle counter (CPC) as the concentration standard (Delene and Deshler 2000). TSI (TSI, Inc.) CPCs are good calibration standards since the counters use a critical orifice to maintain a constant volumetric flow and count individual particles. The accuracy of the TSI CPC is confirmed before CCN counter calibrations using a bubble flow meter primary standard (Sensidyne Gilibrator-2). To ensure that the CPC and CCN counters detect the same particles, a differential mobility analyzer (DMA) is used to size-select from a poly-dispersed ammonium sulfate particle stream (Bart and Delene 2013; Delene and Starzec 2014). The DMA uses electrical mobility to select particles over a very narrow size range (Kulkarni et al. 2011, Chapter 15) that excludes particles that do not activate at the CCN counter's supersaturation. When the DMA selects small diameter particles, for example 20 nm diameter, the UWyo CCN counter 1.0 percent supersaturation (theoretical value) measures is less than 20 cm^{-3}, which is the noise level of the counter (Delene and Deshler 2000).

The single supersaturation calibration (Delene and Starzec 2014) conducted in January 2011 by UND differs by more than 50 percent at concentrations between 2000-3000 cm^{-3} from the calibration conducted in May 2008 by the University of Wyoming (Figure 6). The University of Wyoming calibrations use the supersaturation spectrum method which requires measurements at several supersaturations and fitting the following equation to the data:

$$C = a * SS^b * (\Delta V) \qquad \text{Eq. 1}$$

where C is the particle concentration, SS is the CCN counter's theoretically determined supersaturation, ΔV is the photo-detector voltage difference between the baseline (particle free) measurement and the peak voltage obtained during the detection cycle, and a and b are fit parameters. During POLCAST, the UWyo CCN counter is operated at a constant theoretical supersaturation of 1.0 percent; hence, equation Eq. 1 reduces to:

$$C = a * (\Delta V) \qquad \text{Eq. 2}$$

While calibrations at 1.0 percent supersaturation are pretty linear, the single supersaturation calibration method can be used to more accurately represent the observed data over all concentrations. The following equation expresses the single supersaturation method.

$$C = A * (\Delta V)^B \quad \text{Eq. 3}$$

Fit parameters *A* and *B* in equation 3 should not be confused with fit parameters *a* and *b* in equation 1 since a different method determines each parameter pair. Equation 1 assumes droplets contribute linearly to light scattering measured by the photo-detector; while, equation 3 allows the amount of light detected per droplet to change with droplet concentration. Hence, equation 3 can model multiple scattering by droplets within the laser beam.

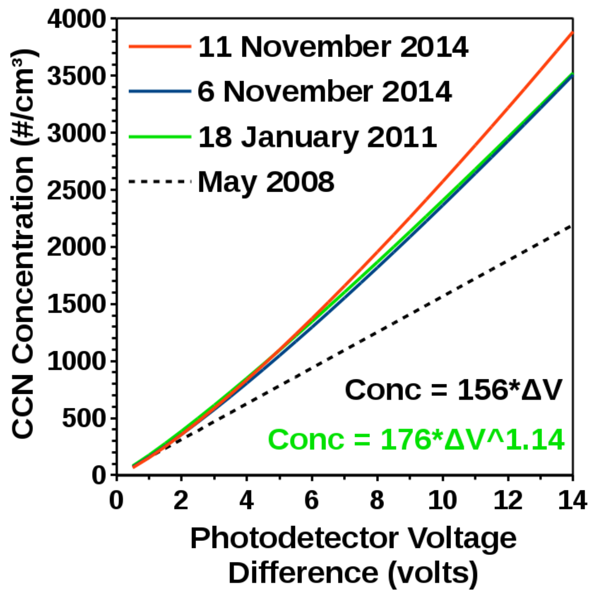

Figure 6: Calibration relationships for the University of Wyoming (UWyo) cloud condensation nuclei (CCN) counter (serial number 107) at 1.0 percent (theoretical value) supersaturation. The dashed line is the calibration conducted by the UWyo using the supersaturation spectrum method while the solid lines are the calibrations conducted by the University of North Dakota (UND) at a single supersaturation. The legend provides the calibration dates. The equations (lower right) provide the relationship between photo-detector voltage difference (ΔV) and the CCN concentration (Conc) for the May 2008 (black) and January 2011 (green) calibrations. Plot created using LibreOffice software.

The supersaturation spectrum calibration method works well when the UWyo CCN counter is operated at several supersaturations during a flight; however, when the supersaturation is constant, the more accurate single supersaturation method can be used. While the calibration difference between May 2008 and January 2011 may be due to different methods, the difference is likely not due to instrument drift since there is little difference in the 2011 and 2014 calibrations (Figure 6). Considering that the May 2008 supersaturation spectrum calibration did not include 1.0 percent and the reproducibility over time of the January 2011 calibration, we use the January 2011 calibration for the POLCAST data set.

It is important to note that this paper's calibrations and measurements are at the CCN counter's theoretical supersaturation of 1.0 percent; however, the actual ambient supersaturation is approximately 0.6 percent (Snider et al. 2006). Such a supersaturation difference is important when comparing to models or observations conducted with other CCN counters. The DMT CCN counter (Roberts and Nenes 2005) uses a different measurement method than the UWyo CCN counter so comparisons can be informative. Additionally, more recent measurements will use the DMT CCN counter since parts are no longer available for the UWyo CCN counter. A comparison between the UWyo and DMT CCN counters show agreement within the counter's uncertainty (Figure 7). We take the combined uncertainty to be greater than 20 percent since the UWyo CCN counter's uncertainty is approximately 10 percent (Delene and Deshler 2000) and the DMT counter uncertainty is at least 10 percent (Rose et al. 2008).

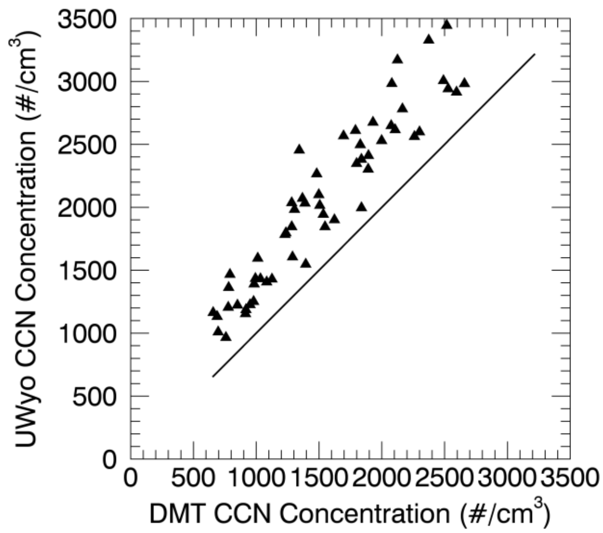

Figure 7: Plot showing measurements from the Droplet Measurement Technology (DMT) cloud condensation nuclei (CCN) counter versus the University of Wyoming (UWyo) CCN counter (serial number 107). Measurements are of poly-dispersed aerosols generated in the lab on 25 June 2014. Concentrations are at standard temperature and pressure conditions using an adjustment to the CCN counters measurement. The solid black line is the one-to-one line. The UWyo CCN counter is using the 18 January 2011 calibration. Plot created using the Airborne Data Processing and Analysis software package (ADPAA).

While the CCN counters agree, the UWyo CCN counter concentrations are approximately 20 percent greater than the DMT CCN counter. A number of factors may account for the systematic difference between the two counters. For example, the UWyo CCN counter may be operating at a higher supersaturation than the DMT CCN counter. Supersaturation difference is only one possible explanation and extensive laboratory work is required to refine the CCN counter's calibrations. Detailed discussion of CCN counter uncertainties is beyond the scope of this paper; however, calibration uncertainties are the focus of current research (Hibert and Delene 2015) and a future paper (Hibert and Delene 2016). Here it is only noted that the counter's agreement is better using the January 2011 calibration than using the May 2008 calibration and that the UWyo CCN measurements should be regarded as having a 10 to 20 percent uncertainty in absolute concentration.

2.4 Data Set Quality Assurance

The POLCAST data set contains raw M300 data files, all derived data files, the science analysis summary files, and additional flight documentation such as pictures, videos, and flight notes. The concepts of missing value codes and meta-data are fully incorporated in the POLCAST data set (Delene 2011). All derived data generated from raw M300 files are in the standard NASA/UND ASCII data format (Delene 2011) which has a meta-data file header that fully describes all parameters contained within the file. The Department of Atmospheric Sciences at UND maintains the complete POLCAST data set on the Citation2 Linux server within a standard directory structure (Delene 2011). The Citation2 server is mountable by workstations throughout the department and backup archives are maintained on and off campus. While the POLCAST data set is not openly accessible online, access is available upon request.

Data quality assurance is defined as the process of reviewing a data set to eliminate (replace with missing value codes) measurements that are invalid due to known problems. The complete POLCAST data set is quality assured by UND scientists possessing the instrumentation expertise relevant to the data under review. Use of an automated process, where programs remove data which does not fall within defined limits, is not employed since not all issues can be addressed in this manner. Furthermore, such an automated process can delay important discoveries; for example, the Antarctic Ozone Hole (Welch 2016). Instead of relying on an automated process, POLCAST scientists employ the ADPAA “Cplot” and “Cplot2” programs (Delene 2016b) to quickly review all important parameters visually.

If a data issue is found, the scientist creates an edit file to address the issue at the lowest possible data level. The edit file stores time periods judged invalid, the scientist's name, the date when the edit is applied, and the reason why data is judged invalid. Data processing software uses the edit file to create a “clean” version of the data file where time periods with identified problems have their “raw” values replaced with missing value codes. The “clean” version of the data is used for all subsequent data processing and thereby incorporated into the science analysis summary file. The interested reader is referred to Delene 2011 for a discussion of airborne data-editing examples, and Delene et al. 2011 for several examples of POLCAST2008 data issues. While removal of all artifacts is impossible, all issues that affect interpretation of the results, such as contamination of background CCN measurements by flare plumes, have been removed from the analysis data set.

3. Results

ADPAA is not only for automated data processing, quality control and quality assurance but also contains programs for conducting data analysis. There are utility scripts that work at the file level to extract, subset, merge, combine, and average data (Sourceforge Wiki). Additionally, there is functionality in Cplot to calculate and store statistics (mean and percentiles) for specific time ranges. The ability of Cplot and Cplot2 to quickly visualize all aircraft parameters at different scales and inter-compare the parameters enable analysis periods to be selected. Furthermore, Cplot2 can quickly create plots at the resolution required for publication (e.g. Figure 8), which is difficult with programs such as Microsoft Excel. Compared to other available tools, ADPAA has three advantages. 1.) Details (e.g. time intervals) of the analysis are documented. 2.) The analysis implementation can be openly reviewed. 3.) The analyses can easily be repeated on the existing data set or applied to another data set.

The quality-controlled and quality-assured POLCAST airborne data set is used to determine the effectiveness of hygroscopic seeding in North Dakota. Airborne observations are analyzed to determine cloud base CCN concentration, temperature and height. Statistical distributions of observations document the natural variability. Such variability, and hence CCN variability, results from localized sources, temporal variations in sinks (e.g. rain), and an atmospheric residence time of days (Singh 1995, Chapter 5). Variability of cloud base temperature and height results from variable water vapor sources and advection, and atmospheric stability. Hence, cloud properties depend on the residence times, sources, and sinks of CCN and water vapor, which can vary greatly spatially and temporally. Therefore, it is necessary to know a region's distribution of cloud base CCN concentration, temperature, and height to enable theoretical understanding (model results) to determine if seeded clouds are likely to produce increased precipitation compared to naturally occurring clouds.

3.1 Cloud Condensation Nuclei

CCN measurements using the UWyo May 2008 calibration have been presented previously for individual POLCAST field projects (Delene et al. 2011; Bart and Delene 2013; Delene and Starzec 2014). Figure 8 shows all the POLCAST CCN measurements, applying the UND January 2011 calibration. Figure 8 depicts a total of 24 flights which is less than the 30 flight tracks given in Figures 1-3 since some days are missing due flights without cloud seeding targets and instrument issues. There are no targets observed on the second flight on 12 June 2008. The CCN counter's inlet has a leak for the 21 June 2008 flight. There is a CCN counter photo-detector issue on 24 June 2010. No targets are observed on the first flight on 02 July 2012, which is a combined test and research flight. There is a wiring issue for the temperature sensor on 17 and 20 July 2012.

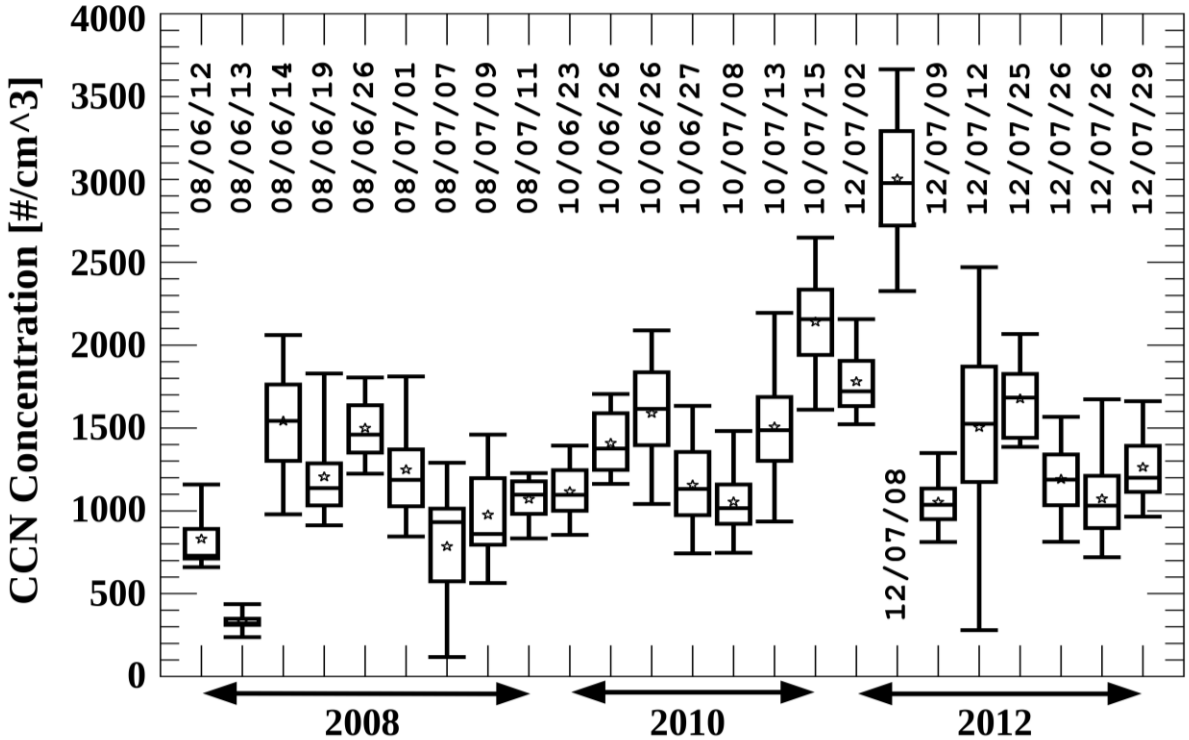

Figure 8: Distributions of cloud condensation nuclei (CCN) below the bases of developing cumulus clouds in North Dakota are shown. Measurements are from the University of Wyoming (UWyo) CCN counter operated at 0.6 percent ambient supersaturation. Concentrations have been adjusted to standard temperature and pressure. Measurements are from 30 s samples obtained throughout aircraft flights lasting up to 4 hours. The x-axis label gives the measurement year and the exact flight date is given in the vertical text (YYMMDD format). Note that there were some days with two flights. Star symbols indicate mean values, horizontal lines denote the 50th percentile, box tops show the 75th percentile, box bottoms mark the 25th percentile, and top and bottom whiskers are the 95th and 5th percentiles, respectively. Plot is created using the Airborne Data Processing and Analysis software package (ADPAA).

There is less variability during each POLCAST day than from day-to-day. The maximum mean CCN concentration observed on POLCAST flights is 3000 cm^{-3}, on 8 July 2012. The minimum mean is 330 cm^{-3}, on 13 June 2008. The overall flight CCN concentration is 1260 ± 500 cm^{-3}. Compared to other observations (Delene and Deshler 2001, Figure 1), POLCAST flight-mean CCN concentrations span is wide, ranging from clean continental to polluted air. The POLCAST mean of 1260 cm^{-3} is twice the concentration observed in West Africa and Saudi Arabia ((Delene et al. 2011, Figure 7). Additionally, the mean POLCAST CCN concentration is larger than lower tropospheric balloon-borne CCN measurements in Wyoming and New Zealand (Delene and Deshler 2001).

The POLCAST observations are similar to daily summer, surface-based CCN mean concentrations of 200 to 1700 cm^{-3} for Western North Dakota (Detwiler et al. 2010). Based on several years of surface-based aerosol measurements at sites around North America (Sherman et al. 2015; Delene and Ogren 2002), one might expect the Western North Dakota CCN concentrations to be similar to those made during POLCAST. The Western North Dakota CCN observation site and the

POLCAST observations are less than 500 km apart and it is only in distinctly different regions that statistics of accumulation mode aerosol concentrations, which relate directly to CCN concentrations, vary significantly. Furthermore, analysis of POLCAST ascent/descent profiles indicate that the atmosphere is well-mixed from the surface to cloud base (Bart and Delene 2013). It is only when surface-based convection is not present or near a large point source that observations of accumulation mode aerosol show a decrease with height above the surface (Andrews et al. 2011; Delene and Deshler 2001).

There is little (<500 cm^{-3}) variation in the observed small scale (10-1000 km) well-mixed lower tropospheric CCN concentration that affects developing cumulus clouds. However, the day-to-day variation is an order of magnitude, from ~300 to 3000 cm^{-3}. Even on two consecutive days when convection occurs, the CCN concentration can change significantly. On 13 June 2008 the mean CCN concentration is 330 ± 60 cm^{-3} but increases to 1540 ± 60 cm^{-3} on the following day. Similarly, the mean CCN concentration is 3000 ± 430 cm^{-3} on 8 July 2012 but decreases to 1050 ± 220 cm^{-3} the following day. As found by Detwiler et al. 2010, CCN concentration changes are not related to different air mass source regions as indicated by 24 hour back-trajectories (Delene et al. 2013). However, rain does lower CCN concentration, at least for several hours, as evident in the 8-9 July 2012 case, boundary layer height may also be important (Delene and Bart 2013), which is investigated in the next section.

3.2 Temperature and Height

Figure 9 shows POLCAST cloud base temperature and altitude measurements for POLCAST days on which CCN concentration measurements are made. The warmest cloud base temperature is 20.3 °C, observed on 29 July 2012. The coldest cloud base temperature is 3.9 °C, on 12 June 2008 and 9 July 2008. The mean temperature of all POLCAST flights is 12.7 ± 5.9 °C. The highest cloud base is 2308 m, encountered on 14 June 2008, and the lowest cloud base is 937 m on the second flight of 26 June 2010. The mean POLCAST cloud base altitude is 1672 ± 408 m.

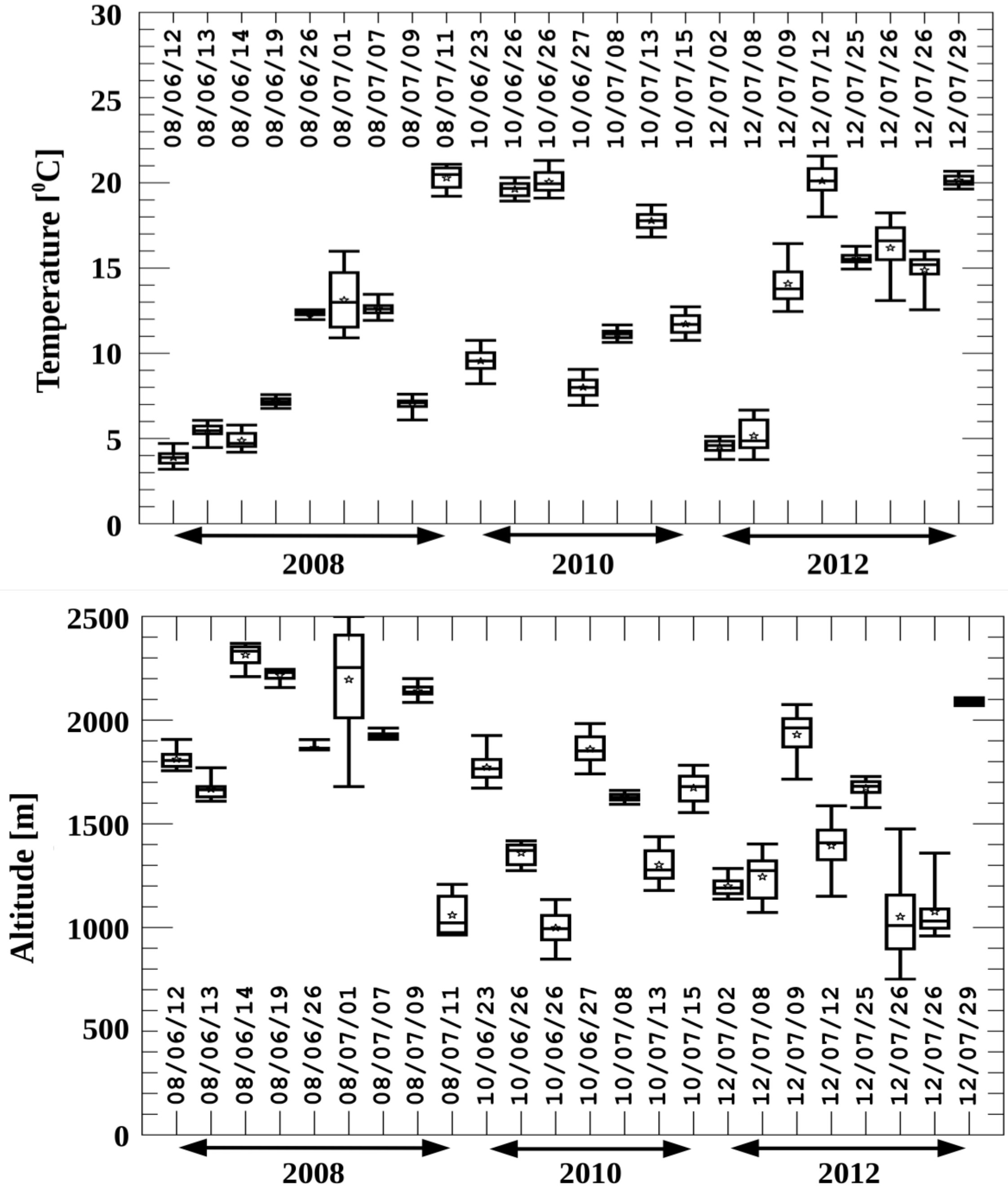

Figure 9: Statistical distributions of ambient air temperature just below cloud base (top) and altitude (bottom) of developing cumulus clouds in North Dakota are shown. Box-and-whiskers and date text are analogous to those in Figure 8. Cloud base altitude is given above mean sea level (MSL). Plot is created using the Airborne Data Processing and Analysis software package (ADPAA).

Grand Forks, North Dakota has a surface elevation of 256 m MSL; hence, approximately 250 m needs to be subtracted from cloud base altitude to obtain cloud base height above the ground (AGL). Therefore, cloud base height AGL ranges from approximately 689 to 2058 m, which is a factor of 3.0 variation. Hence, variations in mixing height could account for a factor of 3.0

variation in day-to-day CCN concentration, assuming the same source rate, sink rate, and horizontal dispersion. However, the POLCAST flight mean CCN concentration and cloud base height have a weak (correlation coefficient of -0.21) relationship. Similarly, cloud base temperature and cloud base height have a weak (correlation coefficient of -0.37) relationship. Therefore, while the 8-9 July 2012 case indicates boundary layer height may be important for predicting CCN concentration, analysis of the complete POLCAST data set indicates that cloud base height itself is not useful for predicting CCN concentration.

3.3 Cloud Droplet Growth

While the Citation Research Aircraft is limited to six POLCAST flights (Figure 2), there are some interesting cloud droplet growth measurements (Figure 10). Note that the aircraft penetrated only at certain altitudes, and cloud base is determined from the ascent/descent sounding. The cloud sampled on 15 July 2010 has a slower droplet growth rate (with height) than those sampled on 13 July and 20 July. While 13 July 2010 and 15 July 2010 (no 20 July 2010 data is available) have a "typical" cloud base temperature and height, the 15 July 2010 CCN concentration is the second highest POLCAST concentration observed. Hence, the 15 July 2010 observations support the concept that high CCN concentration results in a high droplet concentration and small droplet size, which take more cloud depth to grow via the condensation process before reaching a sufficient size (approximately 24 µm) to initiate the coalescent process (Rosenfeld et al. 2008).

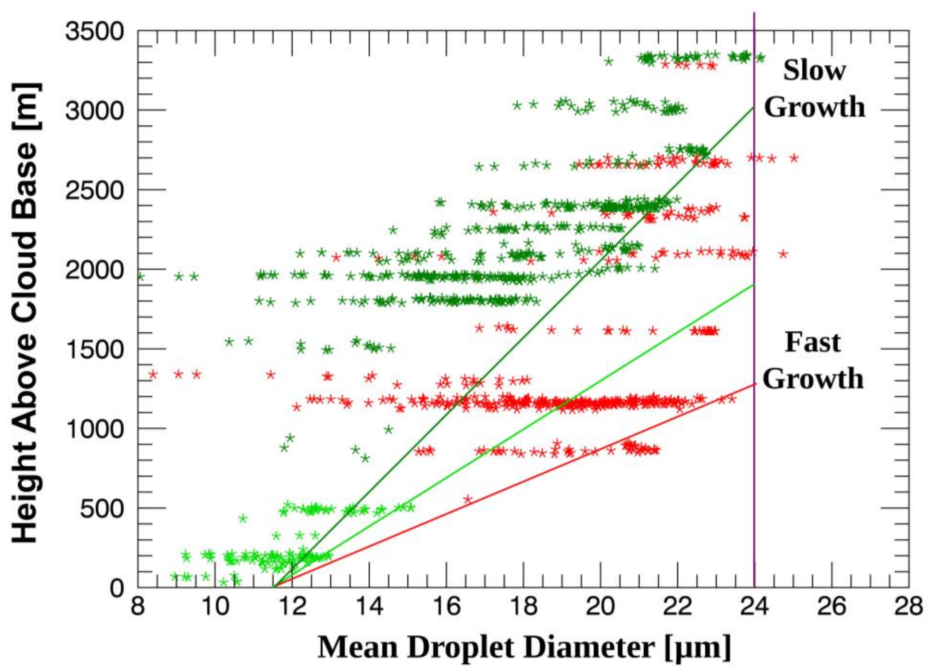

Figure 10: The cloud droplet probe (CDP) mean droplet diameter versus the height above cloud base for aircraft flights near Grand Forks, North Dakota in the summer of 2010 (light green – July 13; dark green – July 15; red – July 20). Only measurements with CDP concentrations above 140 cm^{-3} are presented. The color (red, light green, and dark green) lines are manually overlaid to show the increase of maximum droplet diameter observed at each penetration level. The vertical purple line denotes where theory indicates coalescence starts to become an efficient growth process. The plot is created using the Airborne Data Processing and Analysis software package (ADPAA) and LibreOffice software.

4. Discussion

4.1 Instrumentation Challenges

POLCAST used many cutting-edge technologies, and unfortunately not everything worked. While scientists are sometimes reluctant to publish information about what did not work in an experiment, it is important that we all learn from each other. The DMT CDP is the latest in the family of forward-scattering probes that measure cloud droplets. POLCAST2008 used a Forward Scattering Spectrometer Probe (FSSP), with DMT's SPP-100 electronics upgrade, to obtain the droplet concentrations that are related to the cloud base CCN measurements (Delene et al. 2011, Figure 8). The CDP has similar electronics as the SPP-100 FSSP; however, the optical system is different. While the CDP is similar to the FSSP, ADPAA required a new data processing module. As with most new instruments, there is a learning curve to understanding the CDP's operations, calibration and quality control procedures.

The POLCAST team conducted CDP probe cleaning and calibration before the 2010 field project (December 16, 2009), and performance checks during the project (e.g. July 26, 2010). The performance checks reveal that the 15 and 30 μm diameter particles are not sized correctly, and thus produce an incorrect spectrum. The issue is a software configuration error, which requires adjustment of the channel boundaries in ADPAA for correct data processing. Even with the channel size adjustment, the CDP-calculated LWC is approximately 50 percent low compared to the hot wire probe LWC. In addition, the total CDP droplet concentration is extremely low compared to POLCAST2008 measurements in similar types of clouds. Other researchers have experienced the same low droplet counts issues (Lance et al. 2010), and the problem is due to not having an optical mask to reject particles that are well outside the instrument's sample volume. Valid droplets within the sample volume have a large probability of being coincident with droplets out of the sample volume (if detected, not masked) and thus being rejected (along with those outside it), which significantly reduces the droplet concentration. The UND CDP now has an optical mask that has solved the low concentration issues; however, it is not possible to correct the POLCAST2010 CDP droplet concentration measurements.

4.2 Suitability for Hygroscopic Seeding

While the POLCAST field projects generated a robust data set of cloud base measurements using instrumentation on the seeding aircraft, it is unfortunate that more above-cloud base measurements are not available. However, POLCAST's limited scope is focused on obtaining cloud seeding targets. The 13/15 July 2010 difference in droplet growth with height is interesting considering that North Dakota clouds may not obtain sufficient depth to produce precipitation under 15 July 2010 conditions. Hygroscopic seeding could be very effective under these conditions by increasing the concentration of large droplets and decreasing the height above cloud base where coalescence begins. Such a hygroscopic seeding effect should be clearly documented by measurements; however, this task is difficult. While POLCAST did not obtain in-cloud measurements that clearly demonstrate seeding effects, stacked flights between the seeding aircraft and the Citation Research Aircraft were conducted, and improving coordination by transmitting the seeding aircraft's position to the Citation worked well.

The POLCAST project observed large day-to-day variation in CCN concentration (Figure 9) likely resulting in important variations in droplet growth rates above cloud base (Figure 10). Therefore, from a cloud seeding operations perspective, it is important to know if a particular day will have high or low CCN concentrations. Since the North Dakota boundary layer is well mixed on days when hygroscopic seeding targets are present and CCN concentrations do not vary significantly on scales of several hundred kilometers and several hours, local surface based measurements can be used to predict afternoon cloud base conditions.

While the POLCAST data set is small, the cloud base, flight mean CCN concentration is Gaussian distributed with one high outlier and one low outlier (Figure 8). The lack of a bi-modal distribution indicates there is no clear stratification. Based on modeling results (Yin et al. 2000) that hygroscopic seeding is effective in environments when CCN concentration (1.0 percent supersaturation) is greater than 500 cm^{-3}, most, if not all days, would be suitable for hygroscopic seeding. The POLCAST measurements are obtained at an ambient supersaturation of approximately 0.6 percent supersaturation; therefore, the concentrations are lower than CCN concentration at 1.0 percent. Furthermore, even reducing the POLCAST CCN concentration by 20 percent (the measurement uncertainty) would result in most POLCAST days having CCN concentration suitable for hygroscopic seeding.

5. Conclusion and Future Work

POLCAST's relatively high CCN concentration (1260 cm^{-3}) supports the conclusion that addition of large hygroscopic particles produces more collector droplets which increases precipitation efficiency. Precipitation efficiency in North Dakota convective clouds is not a simple warm rain process but is more complex involving more graupel production in the cold cloud region since cloud base temperatures are relatively cold and clouds are several kilometers thick. POLCAST observations show that cloud base heights are relatively close to the surface which indicates that increases in precipitation results in increased rain reaching the surface. All environmental factors examined indicate that North Dakota is suitable for conducting hygroscopic seeding to enhance precipitation. Details of the onset of the coalescent process is impossible to evaluate since the current POLCAST aircraft observations are mostly near cloud base and C-band radar observations, while important tools for validating the seeding conceptual model (Krauss et al. 2010), are likely insufficient.

Several assumptions in the conceptual model require additional observations and further research to validate. A complete aerosol/cloud physics data set for North Dakota would provide a valuable resource for constructing a sufficiently accurate model, so that precipitation changes resulting from cloud seeding could be reliably determined. Development, validation, and use of a model with an established uncertainty may be a more cost-effective method for determining precipitation increases from seeding than a randomized seeding experiment. Use of models with unknown uncertainties is typically accepted in other areas of atmospheric research such as climate change. Additionally, with the limited success of the Wyoming randomized cloud seeding experiment, understanding the physical processes sufficiently to validate a precipitation forecast model is gaining support as the most productive path forward to determine cloud seeding effects (Tessendorf et al. 2015). The conceptual cloud seeding model forms the framework for understanding physical processes which can be subsequently incorporated into a precipitation forecasting model. A model, validated for a specific region, could be used to simulate an operational program for a particular season and determine the expected precipitation enhancement. Caution should be taken when using such simulations, for though it is relatively easy to add a seeding module to a forecast model (Xue et al. 2013), it is considerably more difficult to prove that the physical processes are accurately represented and the model is producing accurate results.

While the physical processes related to hygroscopic seeding of convective clouds are more complex than AgI seeding of orographic clouds, it is also more difficult to conduct a successful randomized hygroscopic seeding experiment (Tessendorf et al. 2010). While existing tools, such as C-band dual polarimetric radars, allow for detection of seeding effects, understanding the physical processes involved in hygroscopic seeding requires observation on small scales, which is becoming available with new instrumentation. The CDP probe with the latest electronics board and a fast RS422 acquisition board enables a 25 Hz data rate while obtaining particle-by-particle information. New cloud imaging probes have 10-15 µm sized diodes that allow for better observations of the onset of the coalescence process. It is now understood how to make airborne DMT CCN counter measurements coupled to the ambient environment and CCN calibration uncertainties are better understood. New measurement techniques (Beals et al. 2015) and laboratory facilities (Shaw 2015) are becoming available. These improvements allow better observations of the physical processes involved in precipitation formation. However, there is still a need for cheaper, smaller, and easier to operate instruments that could be routinely deployed on seeding aircraft to obtain more observations than are possible in a typical research program.

Simultaneous detection of a tracer is very useful to prove a seeding effect is being observed; however, in cloud tracer detection is difficult due to the large (maybe as much as 10^6) dilution factor involved and did not provide results during POLCAST2010 even with a large investment of time to get the SF_6 analyzer installed and operating. SF_6 has the advantage that there are no natural sources so any observed SF_6 would clearly be from the seeding aircraft emissions. Runjun Li at Texas A&M University built the SF_6 analyzer by putting an oxygen and water vapor removal system in front of an electron capture detector (ECD). The SF_6 analyzer can be improved by adding a relative humidity and oxygen detector upstream of the ECD to aid in trouble shooting problems. To avoid the time required and complexity of an SF_6 analyzer, another tracer, such as number concentration of nucleation mode aerosols maybe a better option. Hygroscopic flares likely produce high concentrations of particles in the 10-20 µm diameter size range that do not activate as CCN and remain as interstitial aerosols inside clouds. A well designed inlet should allow detection of these particles; however, it is not clear that the concentration would be sufficiently large to eliminate a natural source.

Instrumentation is not the only area of recent improvement. Data processing and analysis software improvements allow handling of more observations. Unlike instruments, software can easily be copied so improvements can quickly be shared among researchers. Also, similar to measurements, software packages can be combined to provide more capability and understanding. For example, we have already utilized Aaron Bansemer's Software for Optical Diode Arrays (SODA) package developed at the National Center for Atmospheric Research with ADPAA (LaRoche 2015). We plan to combine ADPAA with Software for Airborne Measurement of Aerosol and Clouds (SAMAC) package (Gagne 2015) developed initially at Dalhousie University. Additionally, modeling software such as WRF has seen significant improvements. The Thompson aerosol-aware scheme (Thompson and Eidhammer 2014) is able to utilize CCN concentration observations and not have to depend on a fixed cloud water parameterization.

With recent improvements in airborne instruments such as faster electronics, higher resolution diodes, and improved software, we are in a better position to implement process experiments to test each chain in the hygroscopic seeding conceptual model. Such experiments would be closely coupled to improvements and testing of precipitation forecast models. With the interest outside the weather modification community for improving precipitation forecasts, additional funding sources for expanding weather modification field projects may be available such as was done in the AgI Seeding Cloud Impact Investigation (ASCII) campaign (Pokharel and Geerts 2014; Geerts et al. 2013). Additionally, process study experiments can be done in small research projects instead of having to conduct a large randomized experiment which requires sufficient resources to obtain enough cases for statistically significant results.

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