Statistical Analysis of the Polarimetric Cloud Analysis and Seeding Test (POLCAST) Field Projects

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Importance of North Dakota Agriculture

- Agriculture is the number one industry of the state, bringing in more than $4.1 billion annually. *(North Dakota Department of Agriculture, 2010)*
- North Dakota farmers are responsible for >50 % of many crops produced in the United States. *(North Dakota Department of Agriculture, 2010)*

Important North Dakota Crops

Crops	% of U.S. Production
Flax	96%
Canola	90%
Durum wheat	68%
Pinto beans	65%
Dry edible peas	64%
Navy beans	46%
Spring wheat	45%
All sunflowers	44%
Confectionary sunflowers	42%

*North Dakota Studies 2011

Economic Impact of Drought or Hail

- Results in loss of income/jobs for North Dakota residents.
- Increases consumer cost when crop loss occurs.
- The 2002 drought resulted in $223 million in crop damages. *(NCSL 2008)*
- The 2006 drought resulted in $425 million in crop damages. *(NCSL 2008)*

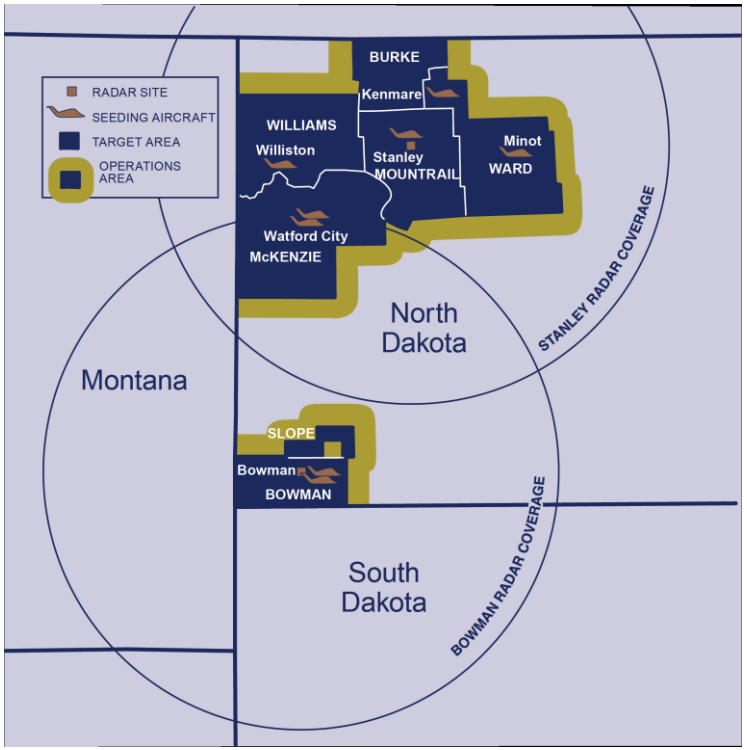
Objectives

Conduct a statistical analysis of the POLCAST randomized seeding field projects in North Dakota.

- Evaluate important environmental factors measured during POLCAST to ensure seed and non-seed cases are from the same population.
- Determine the ratio of radar derived rain rate and rain amount from seeded cases to non-seeded cases.
- Calculate the number of cases required to obtain a statistically significant result ($p<0.05$).

Current Seeding in North Dakota

- Silver Iodide (AgI) seeding has been used since 1950's.
- Operational seeding is conducted in 6 counties in western North Dakota.
- Hygroscopic seeding has not been tested in North Dakota.



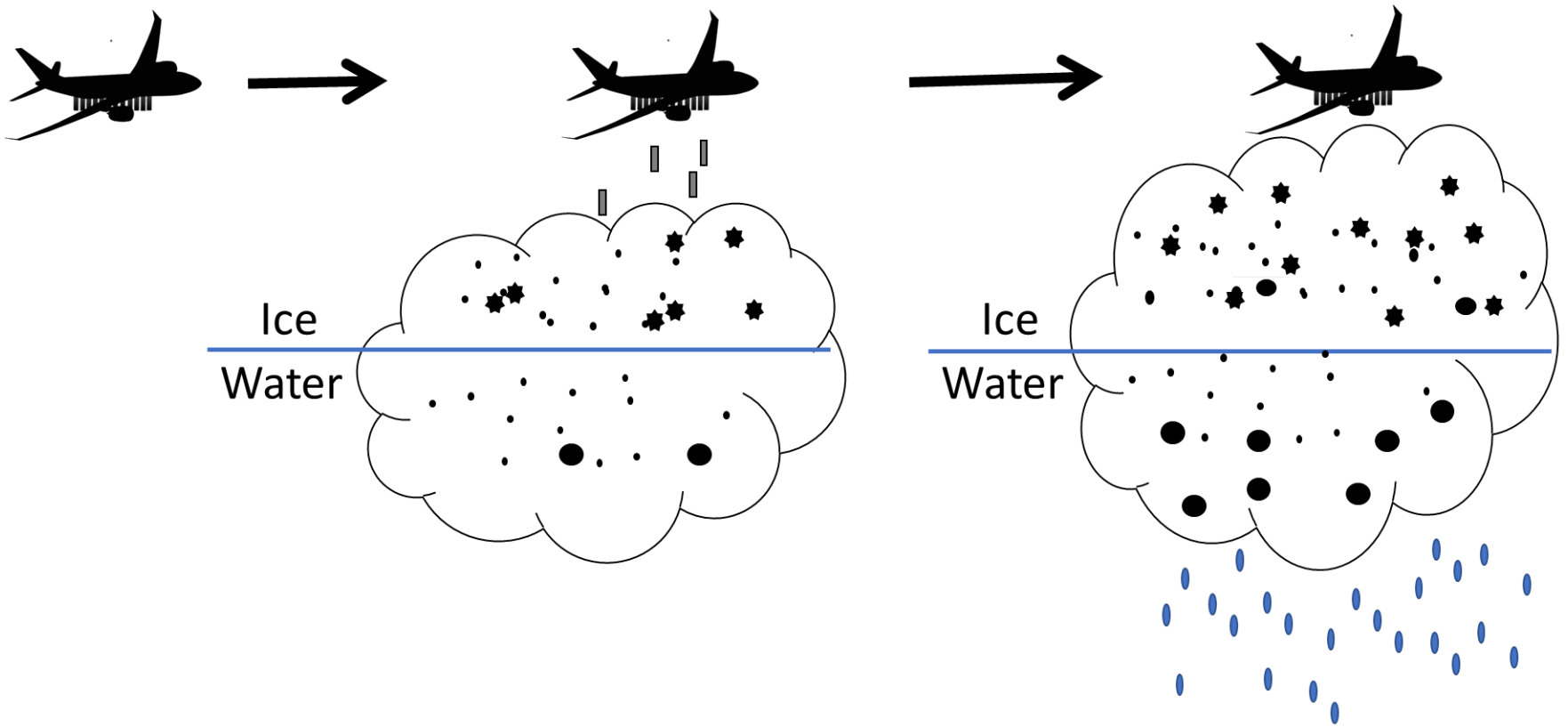
Types of Operational Cloud Seeding

Ejectable

AgI Generator

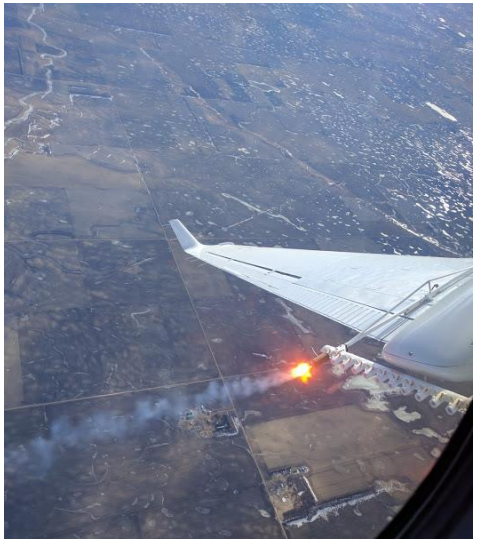
Burn-in-Place

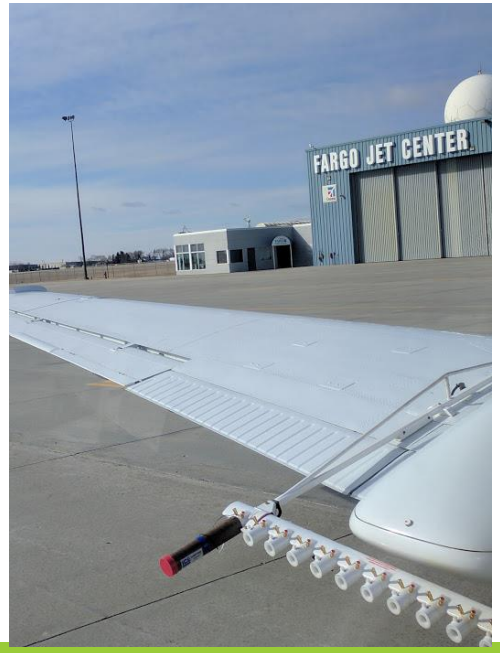
AgI Seeding with Ejectable Flares



$CaCl_2$ Hygroscopic Burn-In-Place

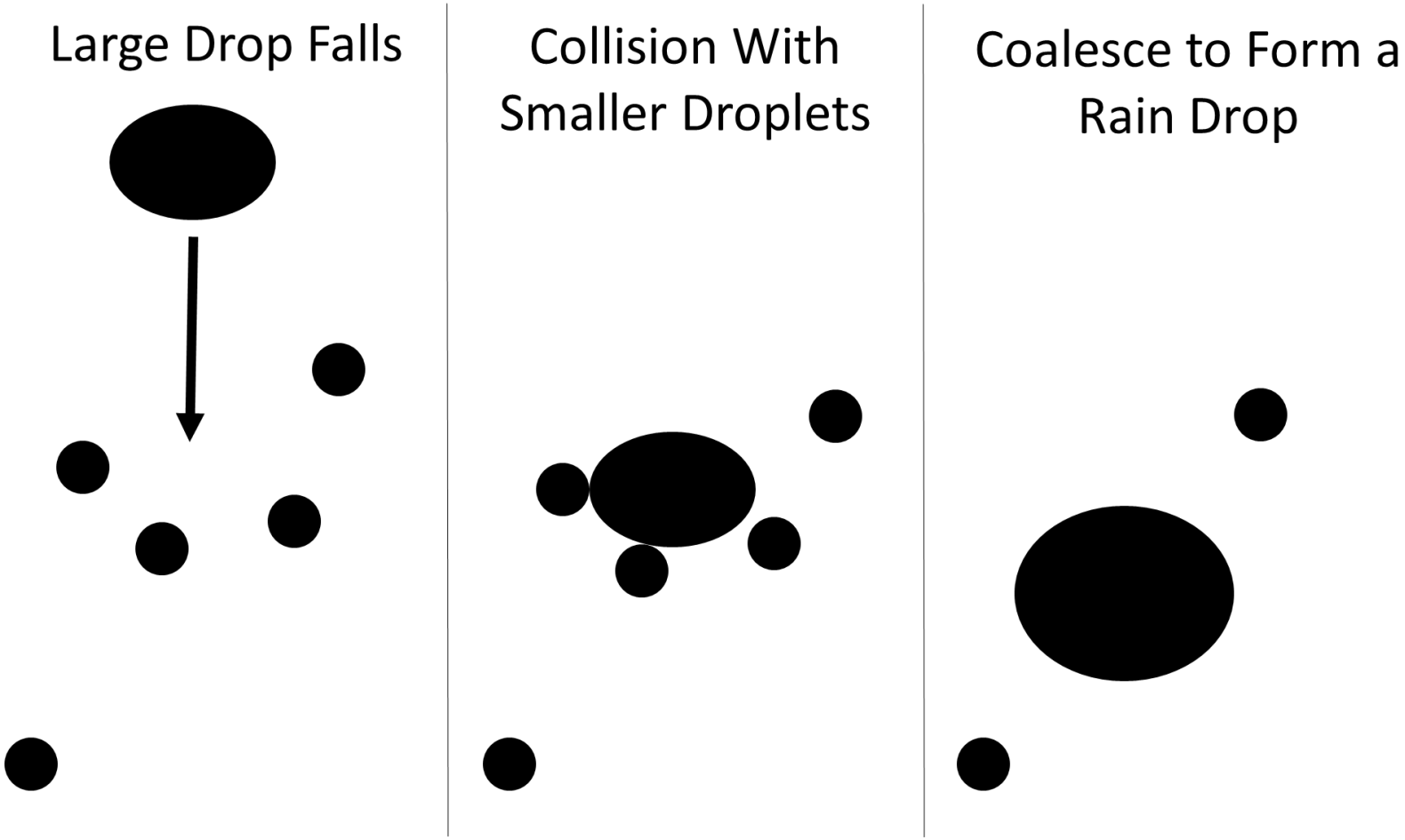
- The sizes of the aerosols, on the order of 5 µm diameter, are the proper size to start the rain process.
- Conceptual model:
  - The addition of hygroscopic particles will enhance the collision and coalescence in clouds with a base above freezing and produce precipitation earlier than naturally occurring.
  - Hygroscopic seeding will cause clouds that would not naturally rain to rain or clouds that would rain to rain more. *(Silverman and Sukarnjanaset 2000)*
- Applications:
  - Rain enhancement by increasing the collision and coalescence process within clouds.



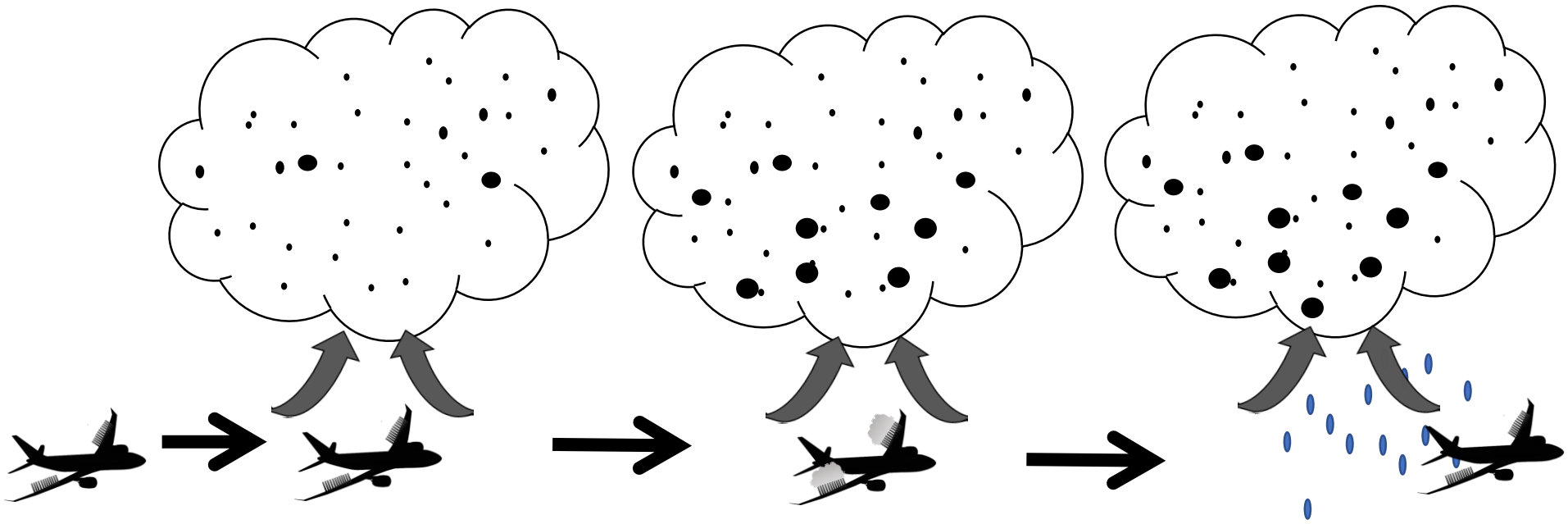


*http://iceflares.com/

Rain Drop Formation: Collision and Coalescence



Hygroscopic Seeding with Burn-In-Place Flares



Hygroscopic Seeding Projects Around the World

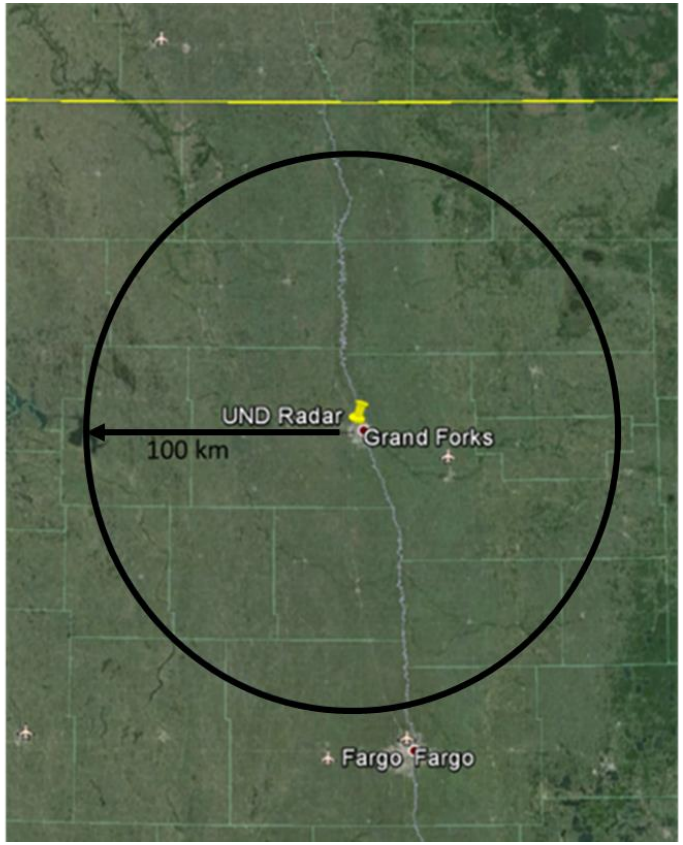
- **South Africa(1991/92 - 1997)**
  - Study began after measuring changes in cloud microphysics downwind of a Kraft Paper Mill. *(Mather et al. 1997)*
- **Mexico(1997-1998)**
  - Study based on findings of South Africa.
  - Seeded clouds found to last longer than non-seeded. *(Silverman 2003)*
- **Thailand (1995-1998)**
  - Best effects were seen in clouds seeded before natural precipitation formation takes place – from model runs.
  - Experimental parameters were chosen to: Maximize the seeding signal and minimize the natural variability.
  - The effectiveness of the seeding could be evaluated with a relatively small sample size.
  - Provided statistically significant evidence of hygroscopic seeding. *(Silverman and Sukarnjanaset 2000)*

POLarimetric **C**loud **A**nalysis and **S**eeding **T**est

- The first POLCAST project in 2006 had the main objective to determine if a radar signature could be seen in clouds seeded with hygroscopic flares.
- Projects in 2008, 2010, and 2012 included random seeding/sampling cloud targets.
- Random seed/sample convective cloud targets within 100 km of the UND radar.
- Cloud base measurements were taken by instruments on the aircraft in seed and non-seed cases.

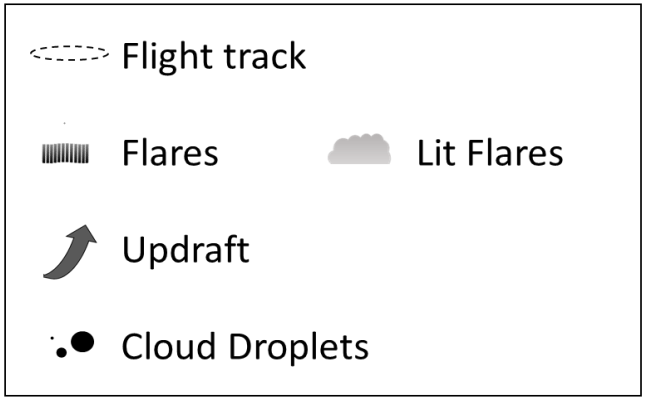
NorthPol C-Band Radar:

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



POLCAST NorthPol Specifications

Surveillance Type	Scan Type	Parameters
Routine	Full-Volume Mode	16 tilts with max elevation of ~22° to a max range of 150 km. Spatial resolution: 250 m Temporal Resolution 10 min
Special: Case has been called	Sector-Scan Mode (1-3 min) centered on the case	High vertical resolution and lowest elevation tilts (elevation ~5°) ensure adequate sampling at low levels and provide high temporal resolution to capture the temporal evolution of the storms



Search

Target

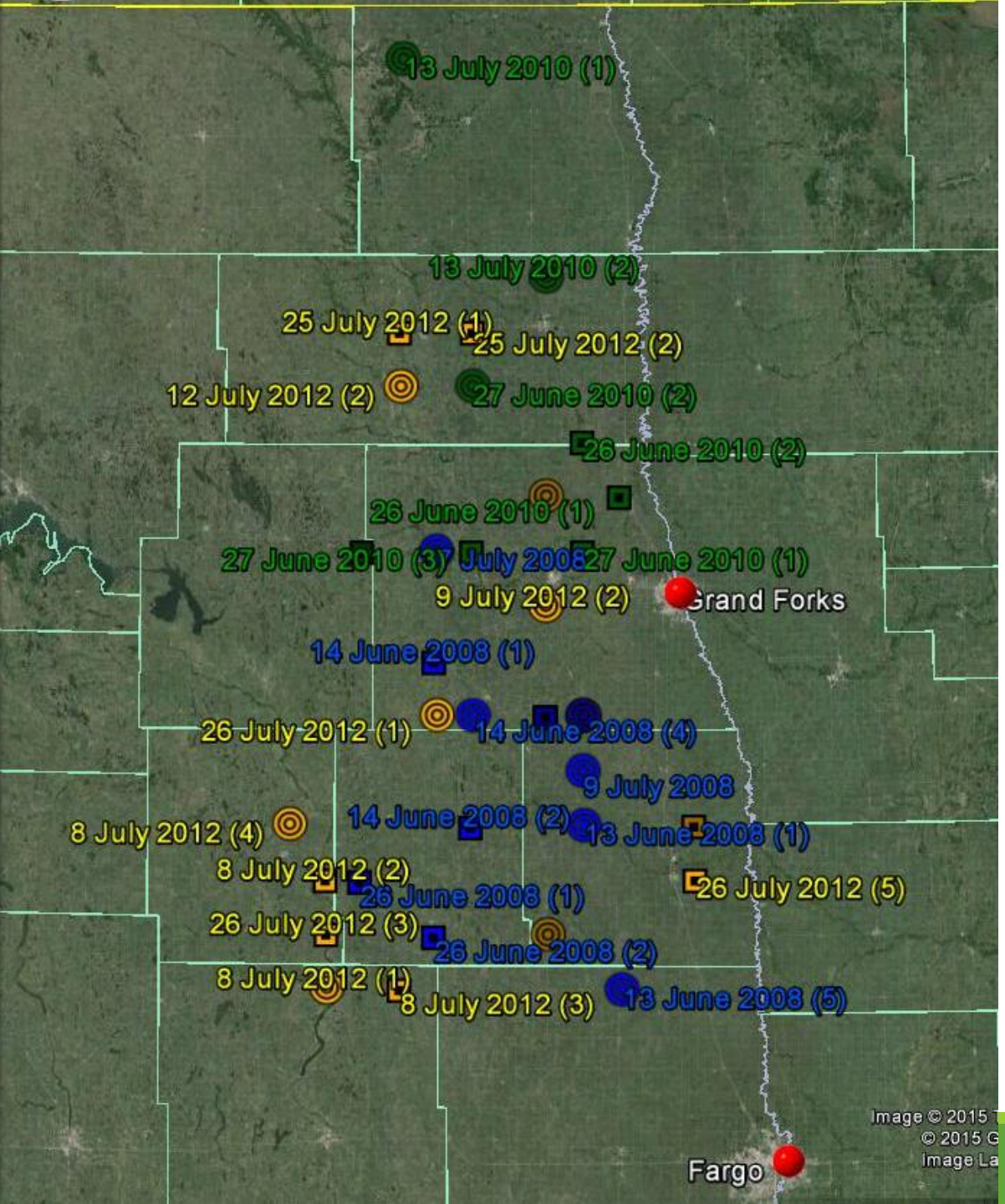
Case

Non-Seeded

Seeded

Requirements for a Case:

- Updraft of 500 ft/min
- Rain free base
- Cloud base temperature between 4-20 ^{o}C
- Evidence of growth in the early stage of development



North Dakota convective cloud targets.

2008

● Seed ■ Non-Seed

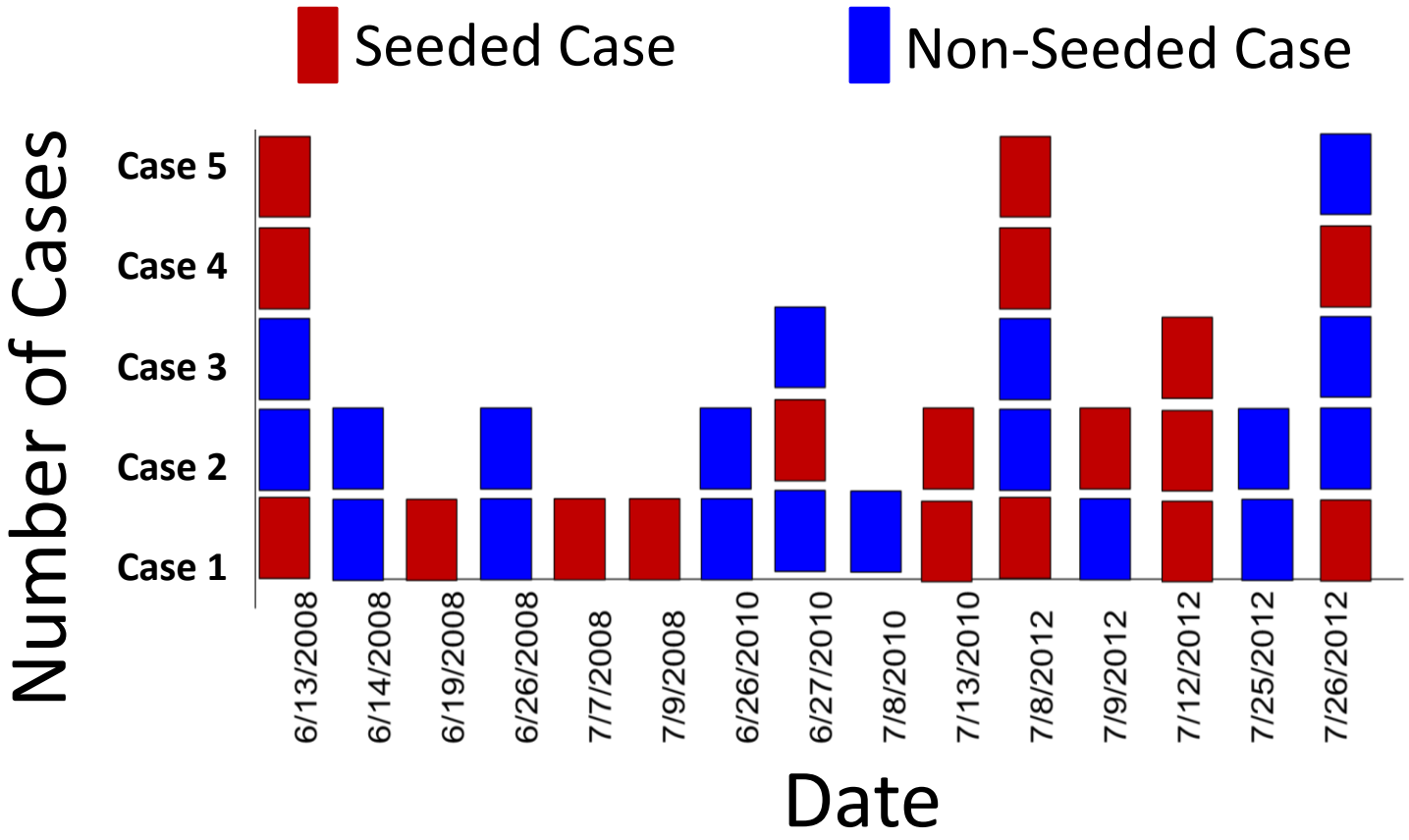
2010

● Seed ■ Non-Seed

2012

● Seed ■ Non-Seed

POLCAST Cases

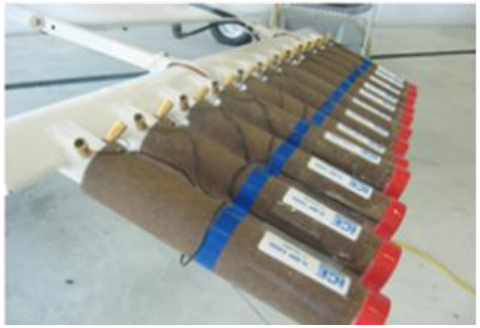


2008	2010	2012
12 Cases	8 Cases	17 Cases
6 Seed and 6 Non-Seed	3 Seed and 5 Non-Seed	9 Seed and 8 Non-Seed

Instruments Used During POLCAST

University of Wyoming Cloud Condensation Nuclei Counter (UWyo CCNC)

Rosemount Aircraft Temperature Sensor



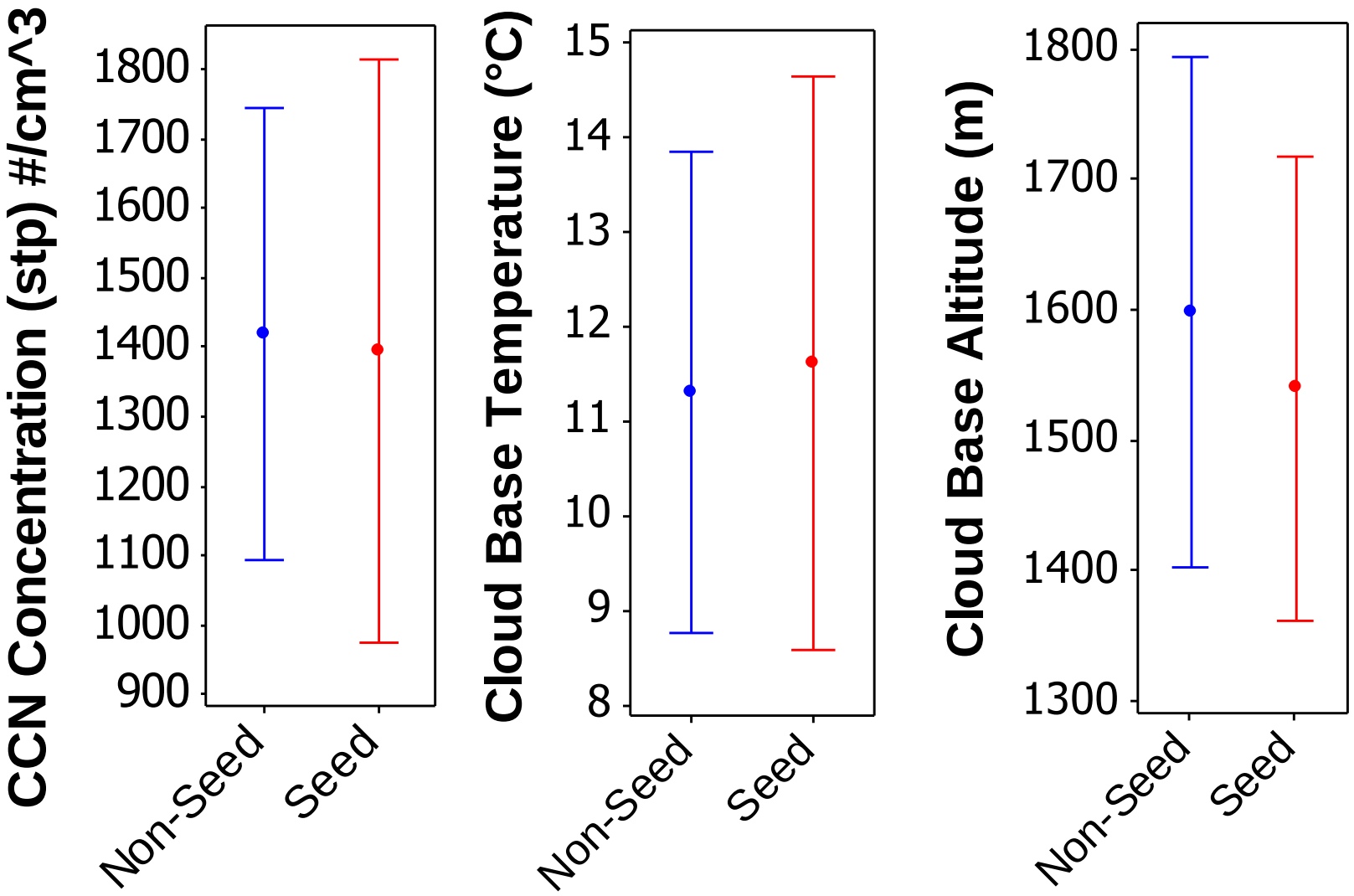
Flare Rack with ICE Hygroscopic Flares

Aventech Aircraft Integrated Meteorological Measurement System (AIMMS)*

*The AIMMS was only used during the last 5 flights of 2012

(Goodrich 2002), (Delene et al. 2011), (Aventech 2017)

Environmental Factors: 2008, 2010, and 2012



Environmental Factors: 2008, 2010, and 2012

Measurement	Average Value: Seed Days	St Dev. Seed Days	Average Value: Non-Seed Days	St Dev. Non-Seed Days	Percent Accuracy
Cloud Base Temperature	11.6 ^{o}C	$\pm$ 0.82 ^{o}C	12 ^{o}C	$\pm$ 0.70 ^{o}C	7.8 %
Cloud Base Pressure Altitude	1673 m	$\pm$ 95 m	1556 m	$\pm$ 80 m	7.3 %
Cloud Base CCNC	1271 #/cm^3	$\pm$ 340 #/cm^3	1381 #/cm^3	$\pm$ 260 #/cm^3	8.3 %

Mann-Whitney Statistical Test

- To show a comparison of cloud base environmental measurements between seeded and non-seeded cases.
  - Cloud base temperature
  - Cloud base altitude
  - Cloud base CCN concentration

Mann-Whitney Statistical Test

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

U=Mann-Whitney U test

n_1 = Sample size one **(seed)**

n_2= Sample size two **(non-seed)**

R_i = Rank of the sample size

Null hypothesis = distributions of both the seed and non-seed cases are identical.

Mann-Whitney Statistical Test

Alpha = 0.05 (two-tailed)

n1\n2	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
2								0	0	0	1	1	1	1	1	2	2	2	2
3								2	3	3	4	4	5	5	6	6	7	7	8
4			0	1	2	3	4	4	5	6	7	8	9	10	11	11	12	13	14
5		0	1	2	3	5	6	7	8	9	11	12	13	14	15	17	18	19	20
6		1	2	3	5	6	7	10	11	13	14	16	17	19	21	22	24	25	27
7		1	3	5	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34
8	0	2	4	6	7	10	13	15	17	19	22	24	26	29	31	34	36	38	41
9	0	2	4	7	10	12	15	17	20	23	26	28	31	34	37	39	42	45	48
10	0	3	5	8	11	14	17	20	23	26	29	33	36	39	42	45	48	52	55
11	0	3	6	9	13	16	19	23	26	30	33	37	40	44	47	51	55	58	62
12	1	4	7	11	14	18	22	26	29	33	37	41	45	49	53	57	61	65	69
13	1	4	8	12	16	20	24	28	33	37	41	45	50	54	59	63	67	72	76
14	1	5	9	13	17	22	26	31	36	40	45	50	55	59	64	67	74	78	83
15	1	5	10	14	19	24	29	34	39	44	49	54	59	64	70	75	80	85	90
16	1	6	11	15	21	26	31	37	42	47	53	59	64	70	75	81	86	92	98
17	2	6	11	17	22	28	34	39	45	51	57	63	67	75	81	87	93	99	105
18	2	7	12	18	24	30	36	42	48	55	61	67	74	80	86	93	99	106	112
19	2	7	13	19	25	32	38	45	52	58	65	72	78	85	92	99	106	113	119
20	2	8	13	20	27	34	41	48	55	62	69	76	83	90	98	105	112	119	127

Mann-Whitney Statistical Test

Alpha = 0.05 (two-tailed)

63	67	72	76
67	74	78	83
75	80	85	90
81	86	92	98
87	93	99	105
93	99	106	112
99	106	113	119
105	112	119	127

Property	Test Statistic (U)	Accept hypothesis?
Mean Cloud Base CCN Concentration	154.5	✓
Mean Cloud Base Temperature	153.5	✓
Mean Cloud Base Altitude	158.5	✓

If U > 106 do not reject the null hypothesis that properties are randomly distributed.

Mann-Whitney Statistical Test

Cloud Base Cloud Condensation Nuclei Concentration		
	Non-Seed Cases	Seed Cases
Number of Cases	19	18
Mean Rank	19.87	18.08
Sum of Ranks	377.50	325.50
Mann-Whitney Test Statistic	154.5	
Significance	**0.621**	

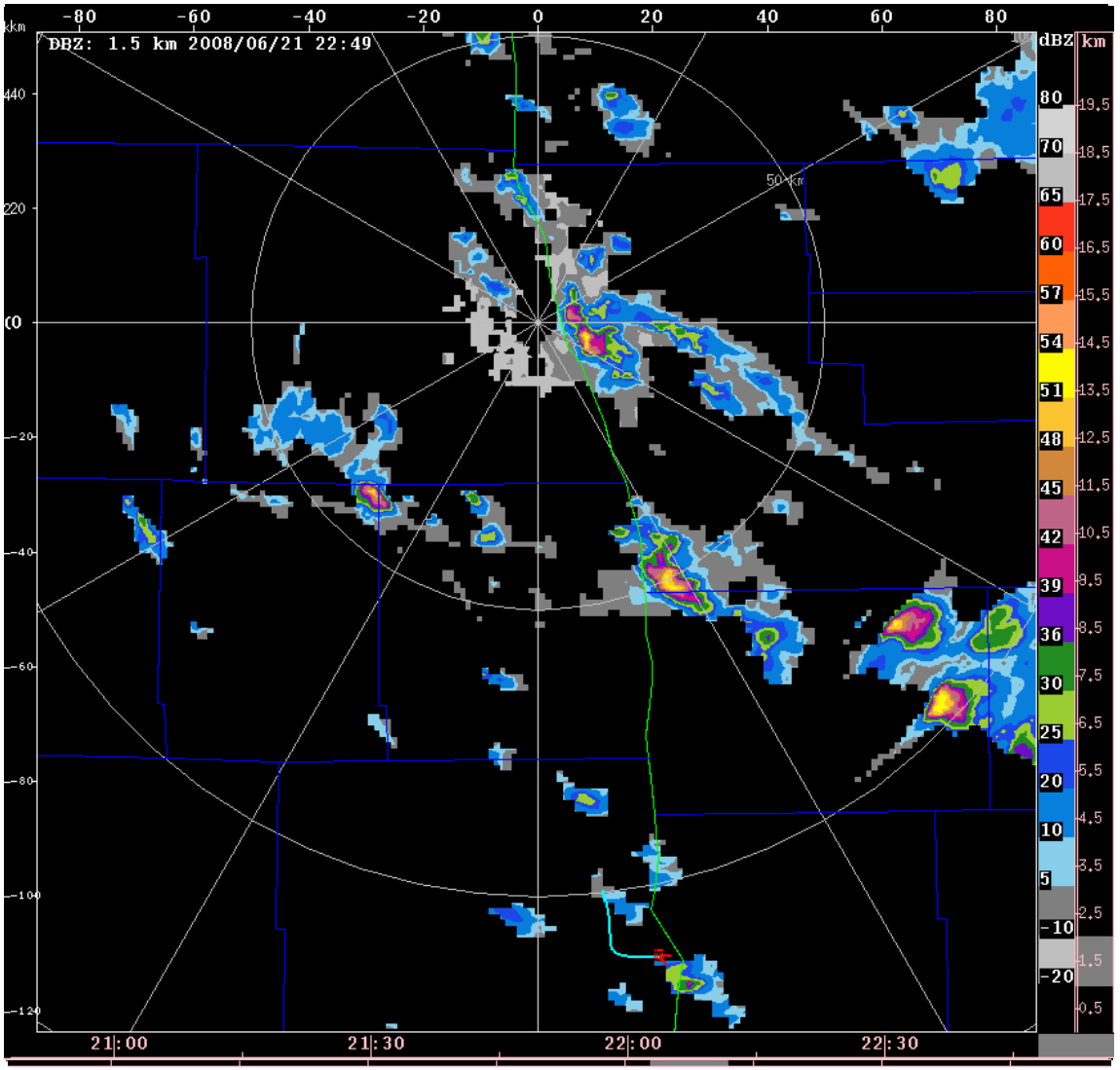
Cloud Base Temperature		
	Non-Seed Cases	Seed Cases
Number of Cases	19	18
Mean Rank	18.08	19.97
Sum of Ranks	343.50	359.50
Mann-Whitney Test Statistic	153.5	
Significance	**0.599**	

Cloud Base Cloud Pressure Altitude		
	Non-Seed Cases	Seed Cases
Number of Cases	19	18
Mean Rank	19.66	18.31
Sum of Ranks	373.5	329.5
Mann-Whitney Test Statistic	158.5	
Significance	**.707**	

- Cloud base environmental factors are evenly distributed between seed and non-seed cases.

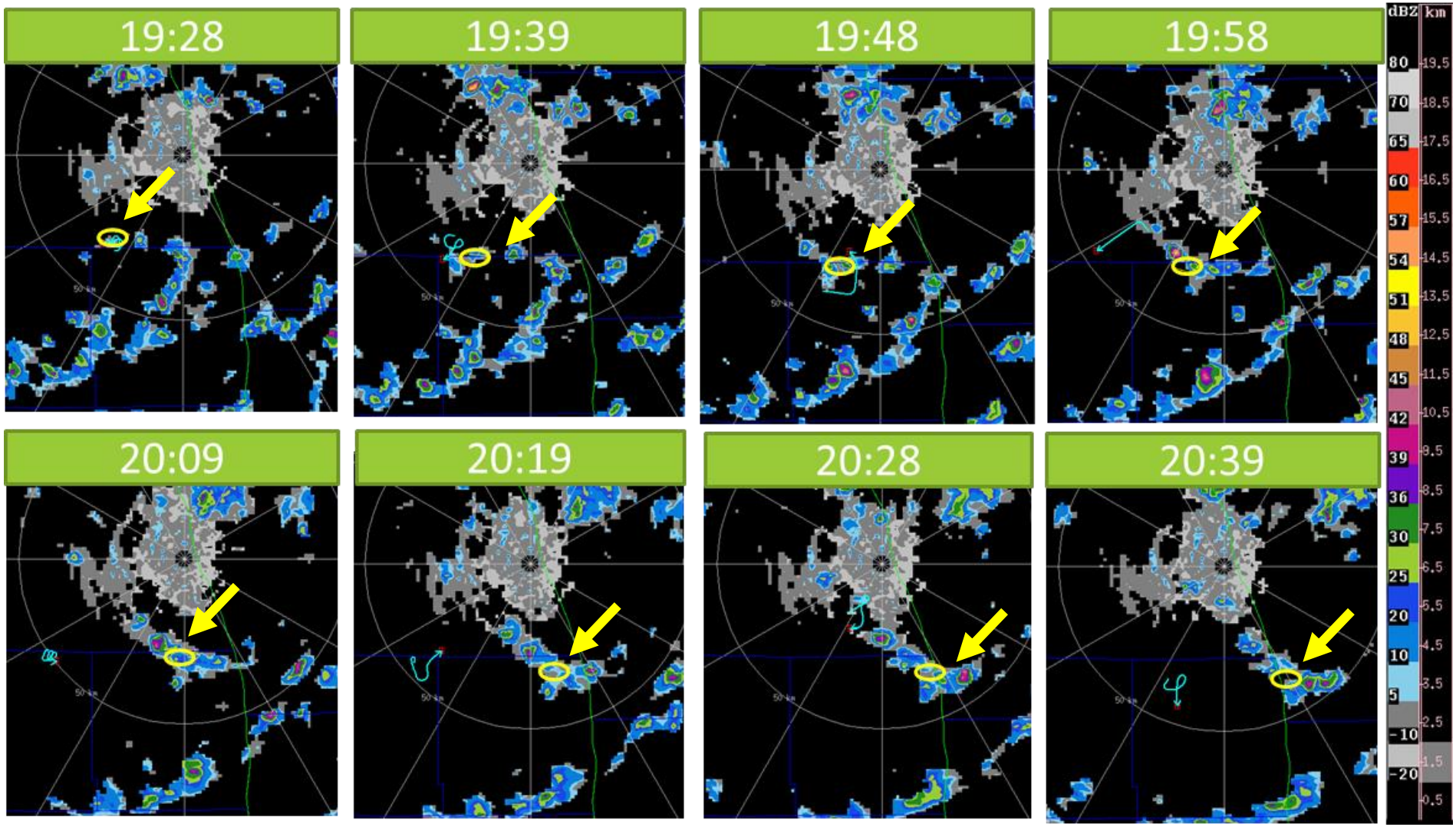
Thunderstorm Identification Tracking And Nowcasting

- Used to track clouds (cases) seeded or sampled by aircraft during POLCAST.

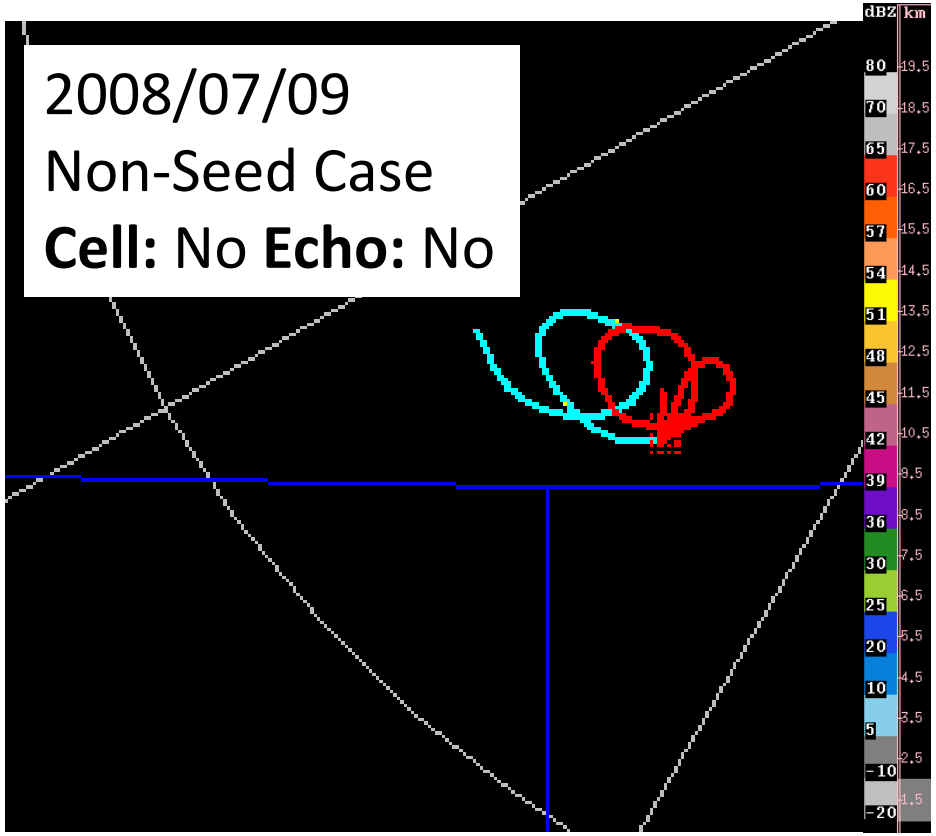


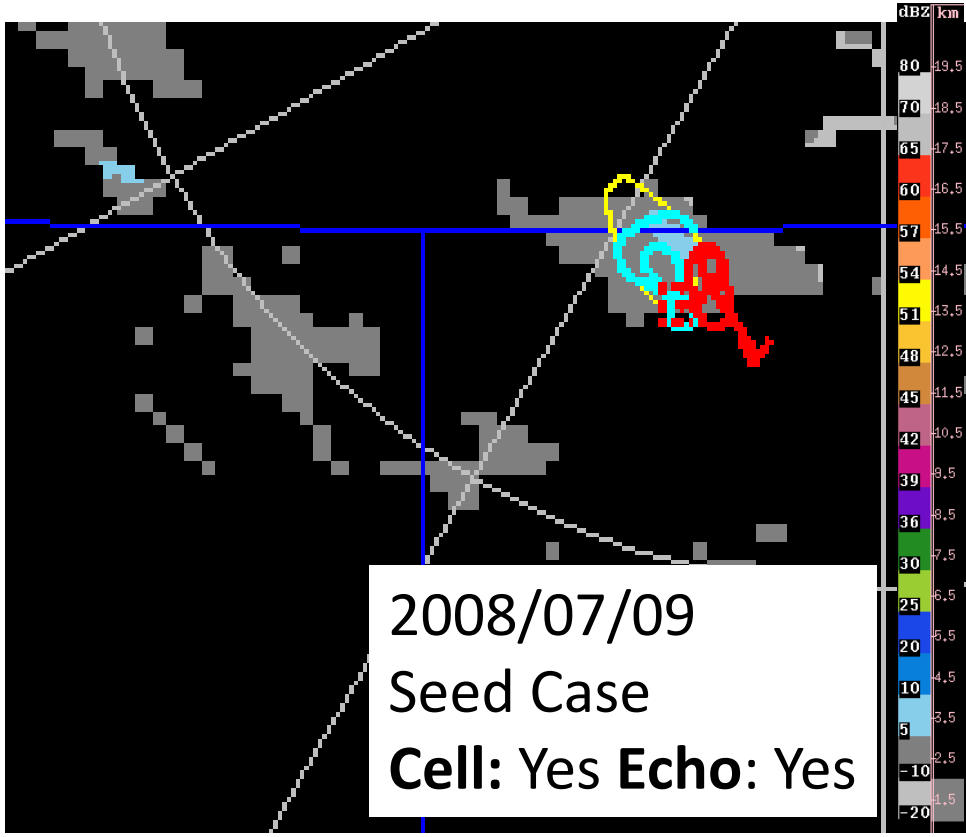
Flight Track on June 21, 2008

June 13, 2008 POLCAST Non-Seed Case

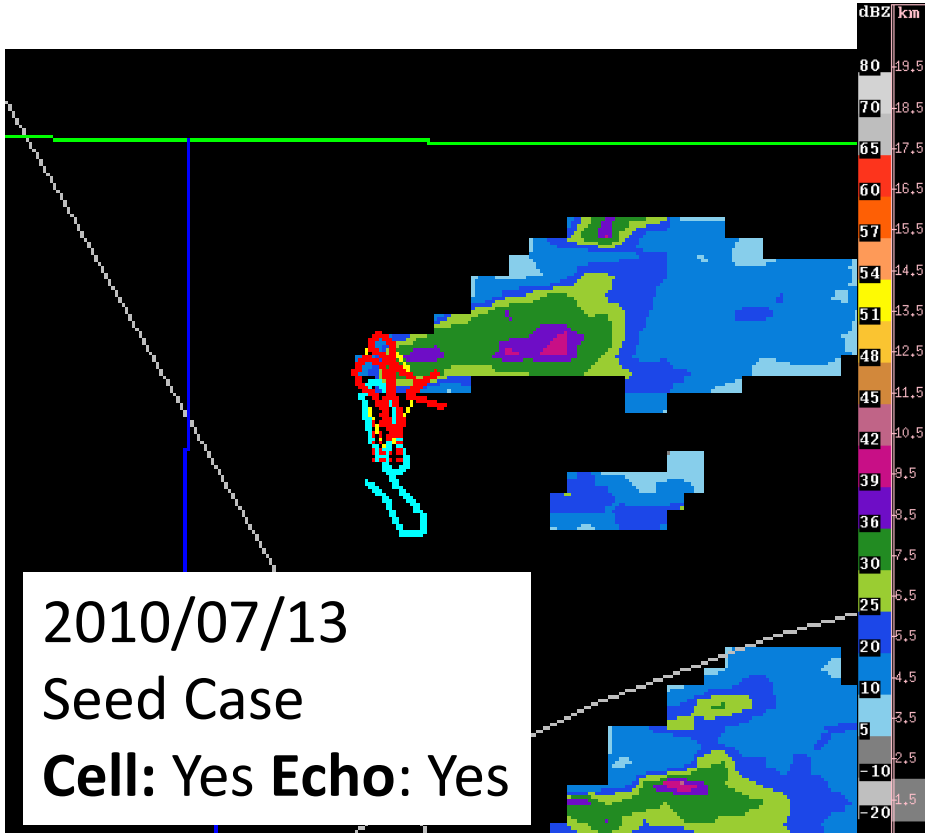


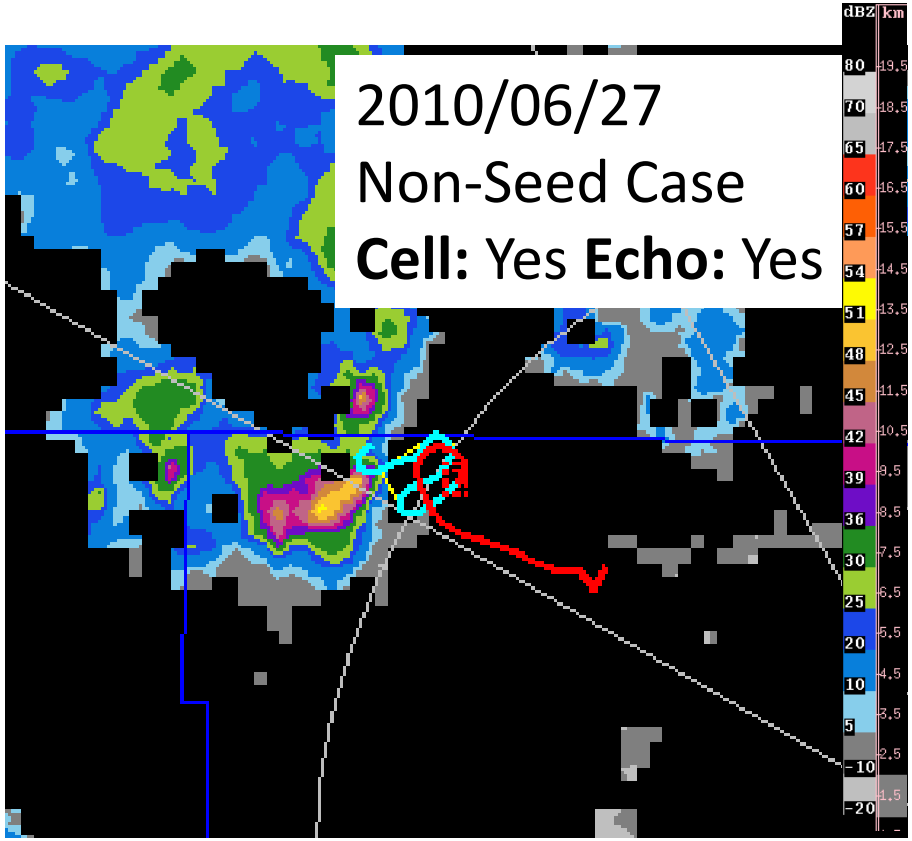
POLCAST2 Case Examples



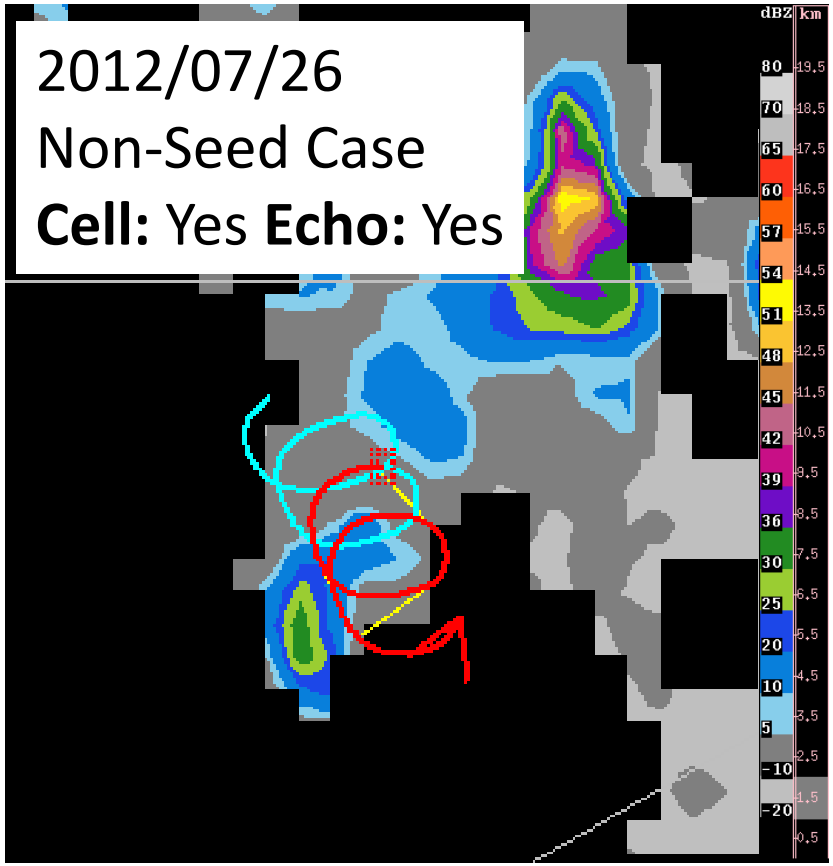


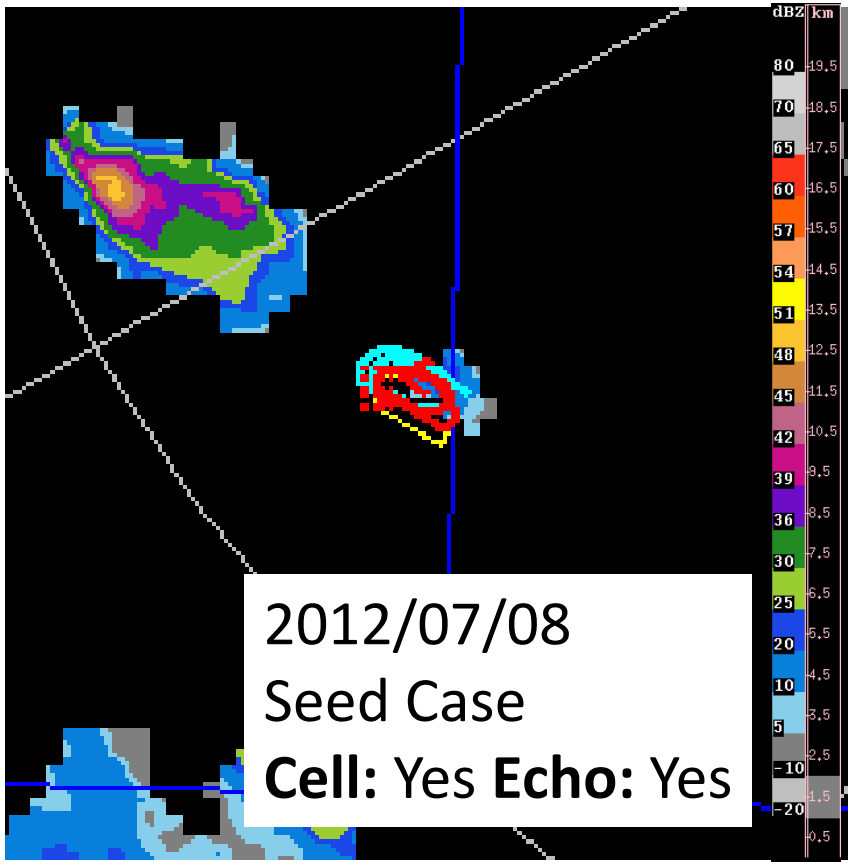
POLCAST3 Case Examples





POLCAST4 Case Examples





Single Ratio and Double Ratio

- Used to show a percent increase of seeded vs. non-seeded cases of chosen variables.

$$Single\ Ratio = \frac{Seed\boldsymbol{X}}{NonSeed\boldsymbol{X}}$$

X = Sample used to compare case measurements

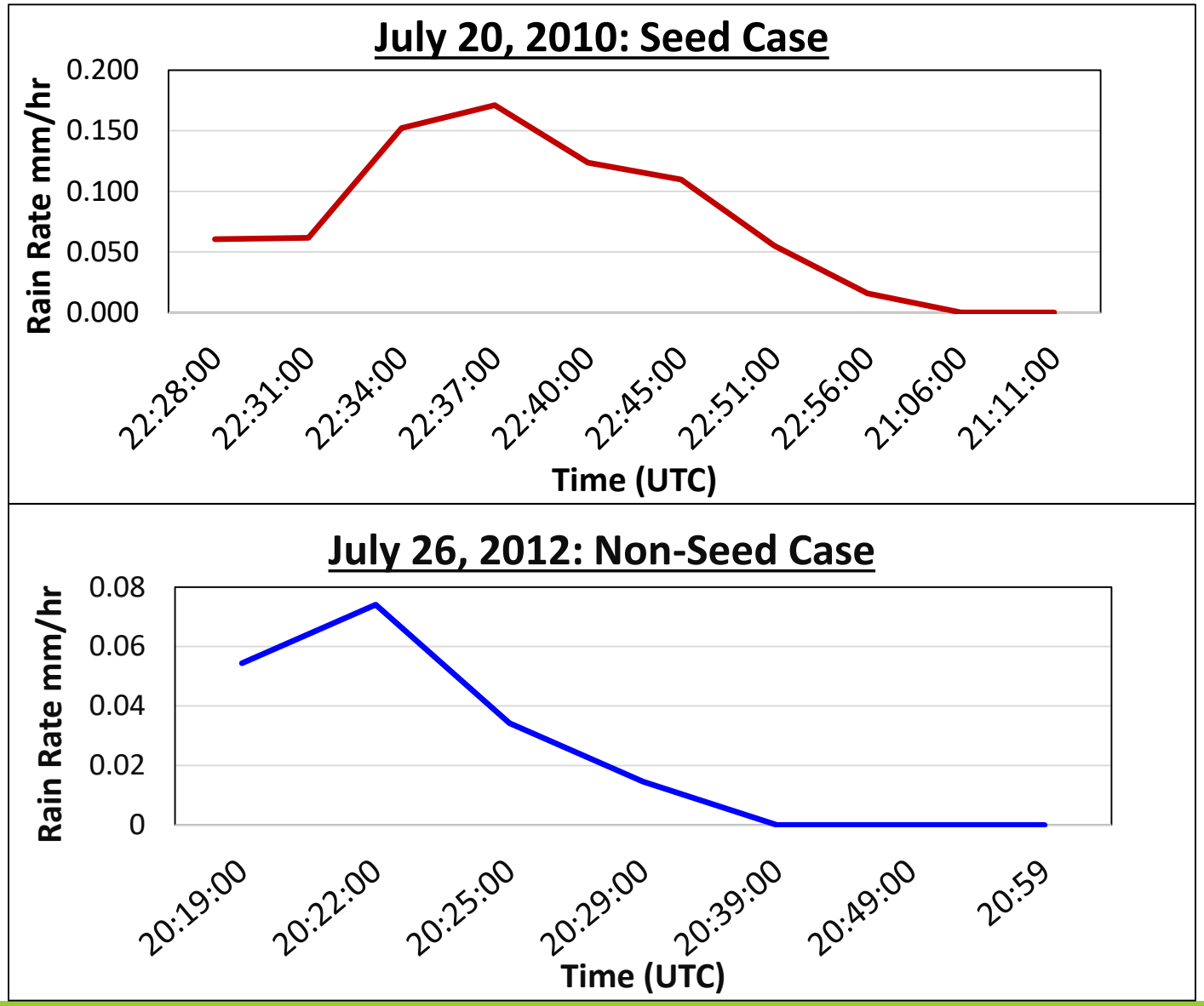
$$Double\ Ratio = \frac{(\frac{Seed\ \boldsymbol{X}}{NonSeed\ \boldsymbol{X}})}{(\frac{Seed\ \boldsymbol{Y}}{NonSeed\ \boldsymbol{Y}})}$$

X = Sum of 30 min-60 min total rain amount past seeding/sampling
Y = Sum of 10 min-20 min total rain amount past seeding/sampling

Single Ratio Results : Reflectivity

Reflectivity (dBZ)	
	SR = Seed Avg/ Non-Seed Avg
10 minutes	1.369
20 minutes	1.266
30 minutes	1.302
40 minutes	1.444
50 minutes	1.000
60 minutes	1.245

Radar Derived Rain Rate



Radar Derived Rain Amount

POLCAST2, 3, 4						
	Seed (Average)	Seed (Total)	Non-Seed (Average)	Non-Seed (Total)	SR = Seed Tot/ Non-Seed Tot	SR = Seed Avg/ Non-Seed Avg
Rain Amount	0.3 mm	4.7 mm	0.2 mm	2.8 mm	**1.7** mm	**1.5** mm

Lifetime of Clouds

Percent of cases lasting 20 - 60 minutes past seeding or sampling					
	Lasted 20 minutes	lasted 30 minutes	lasted 40 minutes	lasted 50 minutes	lasted 60+ minutes
Seed Cases	100 %	88 %	82 %	76 %	41 %
Non-seed Cases	88 %	62 %	56 %	31 %	25 %

Effectiveness of Hygroscopic Seeding in North Dakota

33 Cases

Double Ratio Rain Amount	P-Value	Single Ratio Average Rain Amount	Seeded Cloud Lifetime 60+ Minutes
1.85	0.31	1.5	41 %

Bootstrapping Method:

- Statistical method of resampling with replacement to take values from an original data set and create data sets of varied numbers from the original data.
- Values from the original data set could be included once, multiple times, or not at all in the created data sets.

Bootstrapping Method

POLCAST2,3,4

- Bootstrap on the original data set of **33 radar cases**.
- Iterate through the original data set to create 100, 1,000, and 10,000 data sets of 66, 132, and 264 cases.

POLCAST4

- Bootstrap on the original data set of **15 radar cases**.
- Iterate through the original data set to create 100, 1,000, and 10,000 data sets of 30, 60, and 120 cases.

Bootstrapped POLCAST Data Set

10,000 Iterations			
	66 Cases	132 Cases	264 Cases
Mean Double Ratio	1.97	1.91	1.88
Standard Deviation	0.81	0.54	0.36
Z-Score	1.20	1.70	2.44
P-Value (Right Tailed)	0.115	**0.045**	**0.007**

Bootstrapped 2012 POLCAST Data Set

10,000 iterations			
	30 Cases	60 Cases	120 Cases
Mean Double Ratio	15.07	15.26	13.89
Standard Deviation	6.50	3.98	2.51
Z-Score	2.16	3.59	5.14
P-Value (Right Tailed)	**0.0152**	**0.0002**	**< 0.00001**

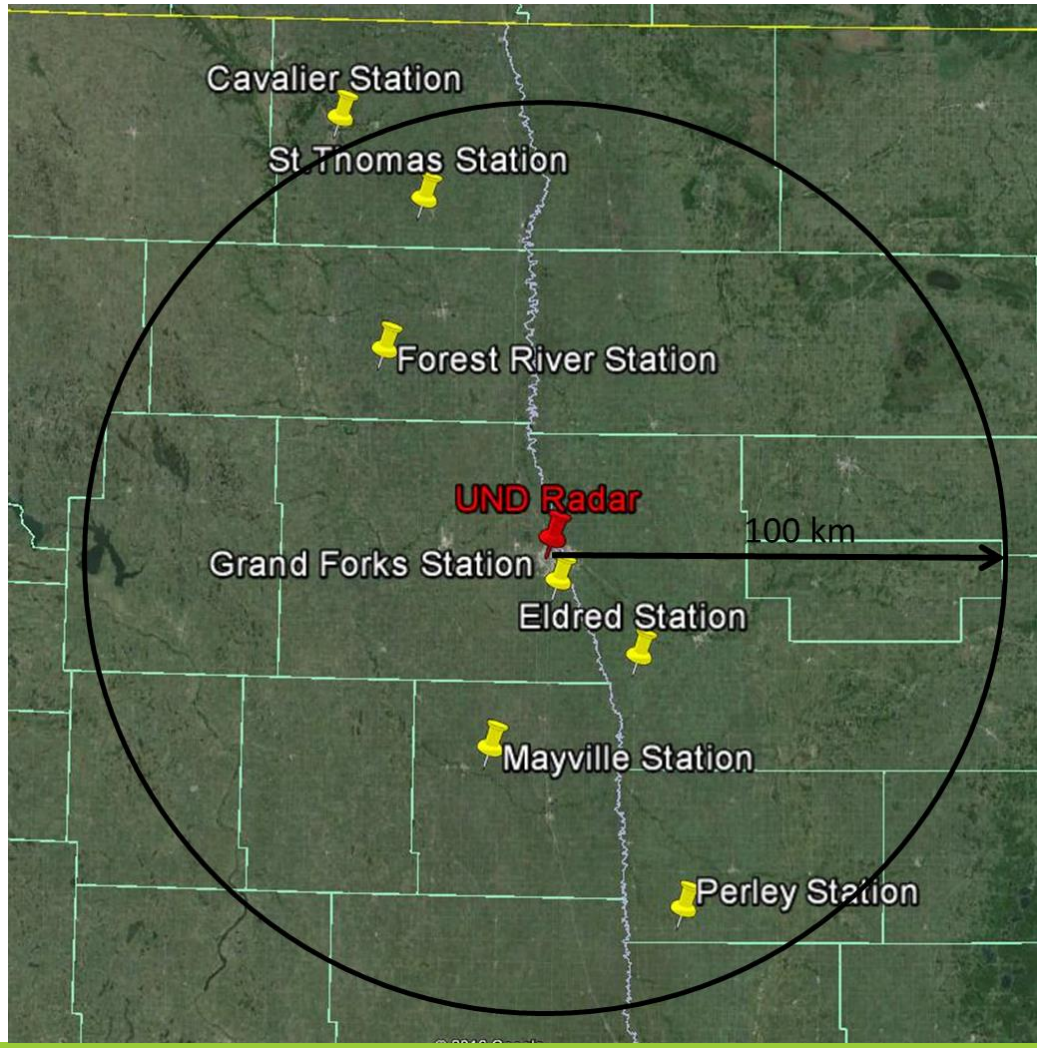
North Dakota Atmospheric Weather Network (NDAWN) Stations

<u>Minnesota:</u>

Eldred, Perley

<u>North Dakota:</u>

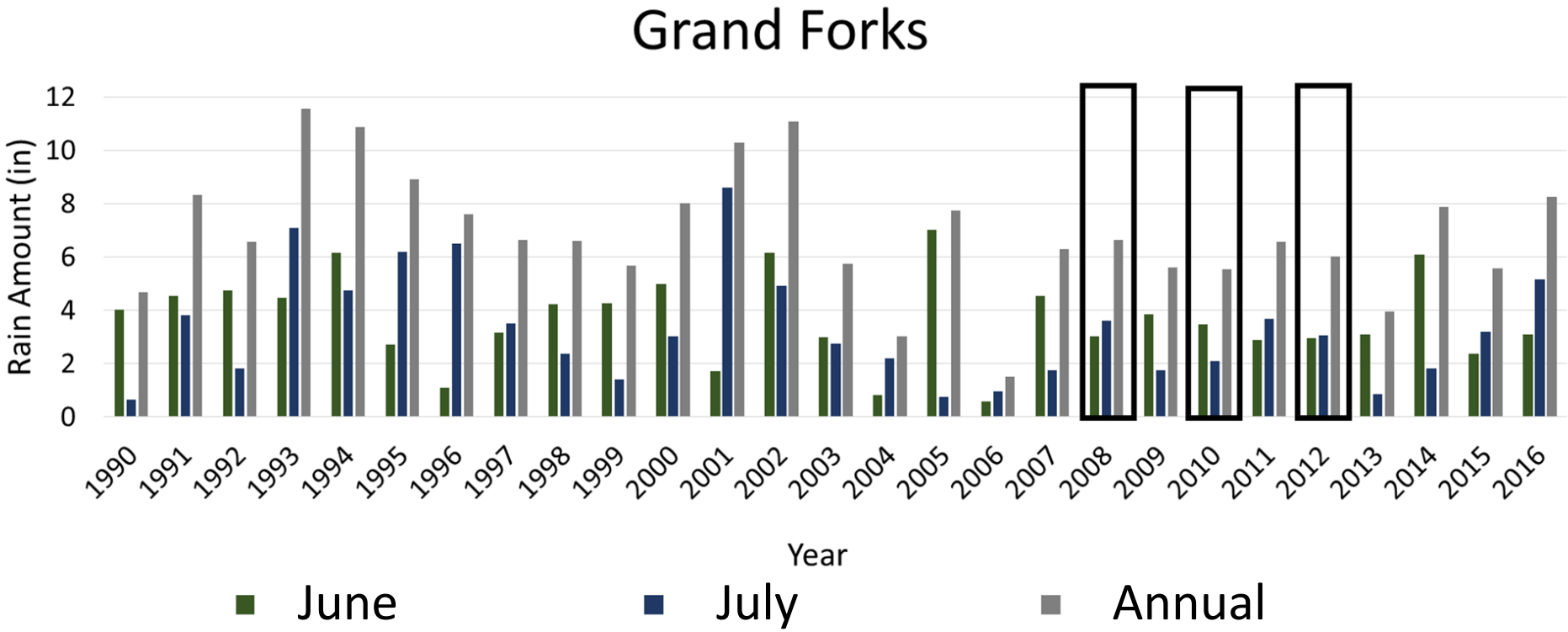
Cavalier, Forest River, Grand Forks, Mayville, St. Thomas



Annual Percentage of Rainfall

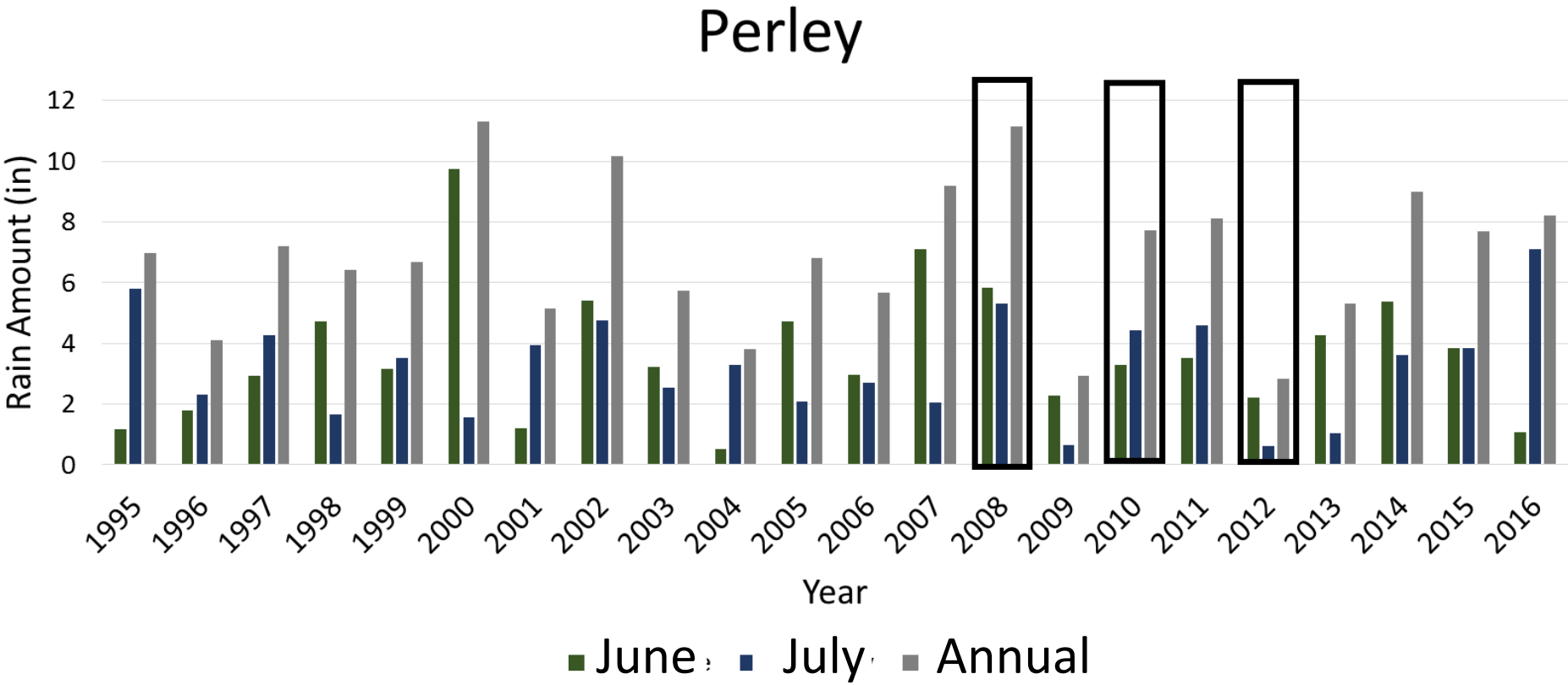
Station and Years of Data	June and July
Cavalier, ND (1993-2015)	39 %
Mayville, ND (1995-2015)	36 %
Grand Forks, ND (1990-2015)	39 %
St. Thomas, ND (1994-2015)	39 %
Forest River, ND (1991-2015)	39 %
Perley, MN (1995-2015)	38 %
Eldred, MN (1995-2015)	38 %

NDAWN: Total Rain Amount in June and July



Rain amount from the Grand Forks NDAWN station to show that the years chosen as seeded were not unusual for the area.

NDAWN: Total Rain Amount in June and July



Rain amount from the Perley NDAWN station to show that the years chosen as seeded were not unusual for the area.

Conclusions

- Environmental factors are distributed in seed and non-seed cases.
- Seeded clouds produced more precipitation than non-seeded clouds.
  - Single ratio = 1.7 and Double Ratio = 1.85.
- Statistical significance was calculated for >132 cases.
- Seeded clouds had longer lifetimes than non-seeded clouds.
  - 41 % of seeded clouds lasting 60+ minutes compared to 25 % of non-seeded clouds.
- There was an increase of rain rate in seeded clouds compared to non-seeded clouds (from TITAN).
- Rainfall in eastern North Dakota was typical during June and July of 2008, 2010, and 2012 when POLCAST took place.

Broader Impacts and Future Work

- Use the Poission Counting Statistic to determine the p-value uncertainty for the number of cases provided.
- Use data, such as environmental factors, from POLCAST to input into a model for simulations of cloud seeding cases.
- Analyze TITAN cells instead of an area of influence.

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  - Leon Osborne
  - Dr. Gerry Dunnigan

- Friends and Family

Silver Iodide (AgI) Flares used in the NDCMP

	AgI Ejectable and Burn-in-Place Flares
Advantages	▪ Wide temperature range spectrum for nucleation ▪ 63 % of nucleation within the first minute ▪ 90 % of nucleation in less than 2 minutes

*http://iceflares.com/

Statistics on 2008, 2010, and 2012 POLCAST Bootstrapped Data Sets

100 iterations				
Cases	66	132	264	528
Mean Double Ratio	1.9243	1.9576	1.8927	1.8420
Standard Deviation	0.7798	0.4838	0.3368	0.2677
Z-Score	1.1853	1.9793	2.6509	3.1452
Test for 1 proportion	.4506	.2688	.1449	.0259

1,000 iterations				
Cases	66	132	264	528
Mean Double Ratio	1.9894	1.9003	1.8710	1.8654
Standard Deviation	0.788	0.4938	0.3513	1.8654
Z-Score	1.256	1.8233	2.4796	3.4901
Test for 1 Proportion	.4194	.2985	.1549	**.0229**

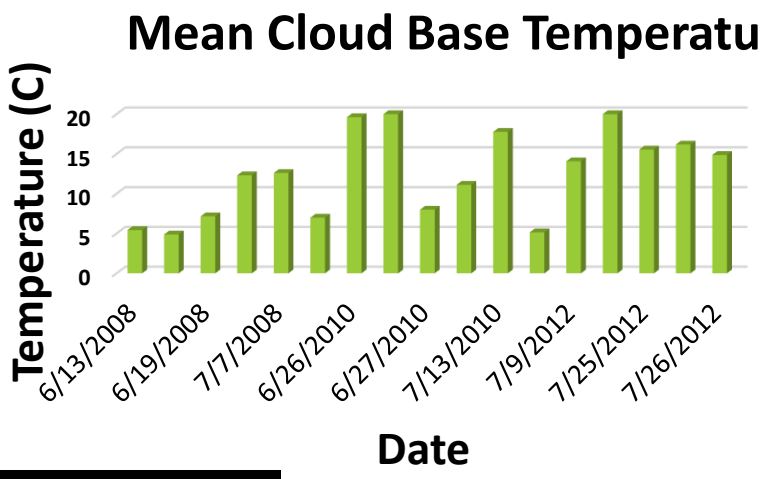
10,000 iterations				
Cases	66	132	264	528
Mean Double Ratio	1.9679	1.9103	1.8814	1.8677
Standard Deviation	0.8070	0.5362	0.3609	0.2536
Z-Score	1.1993	1.6975	2.4421	3.4214
Test for 1 Proportion	.2147	.1466	**.0751**	**.0023**

$$z = \frac{p - p_{exp}}{se(p)}$$

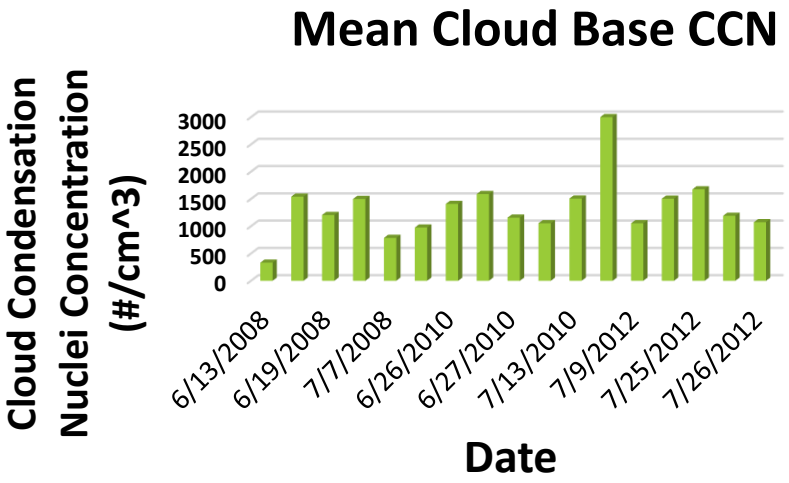
$$se(p) = \sqrt{\frac{p_{exp}(1 - p_{exp})}{n}}$$

Equations for the test for 1 proportion

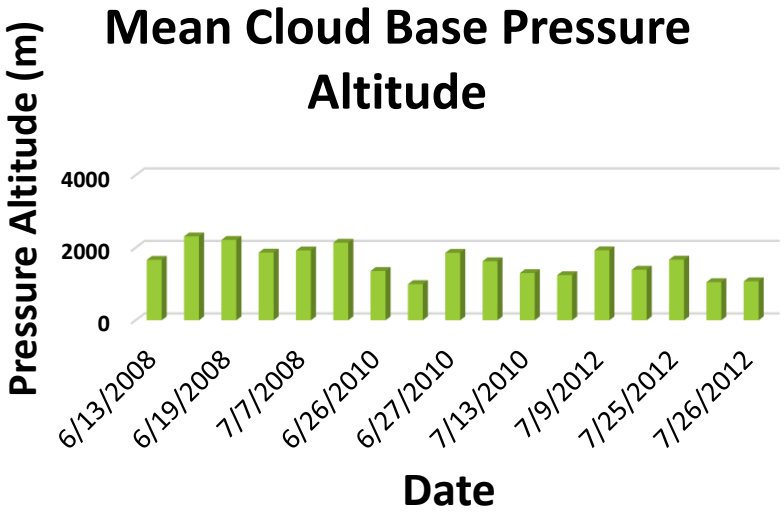
Environmental Factors: 2008, 2010, and 2012



Average = 13 C

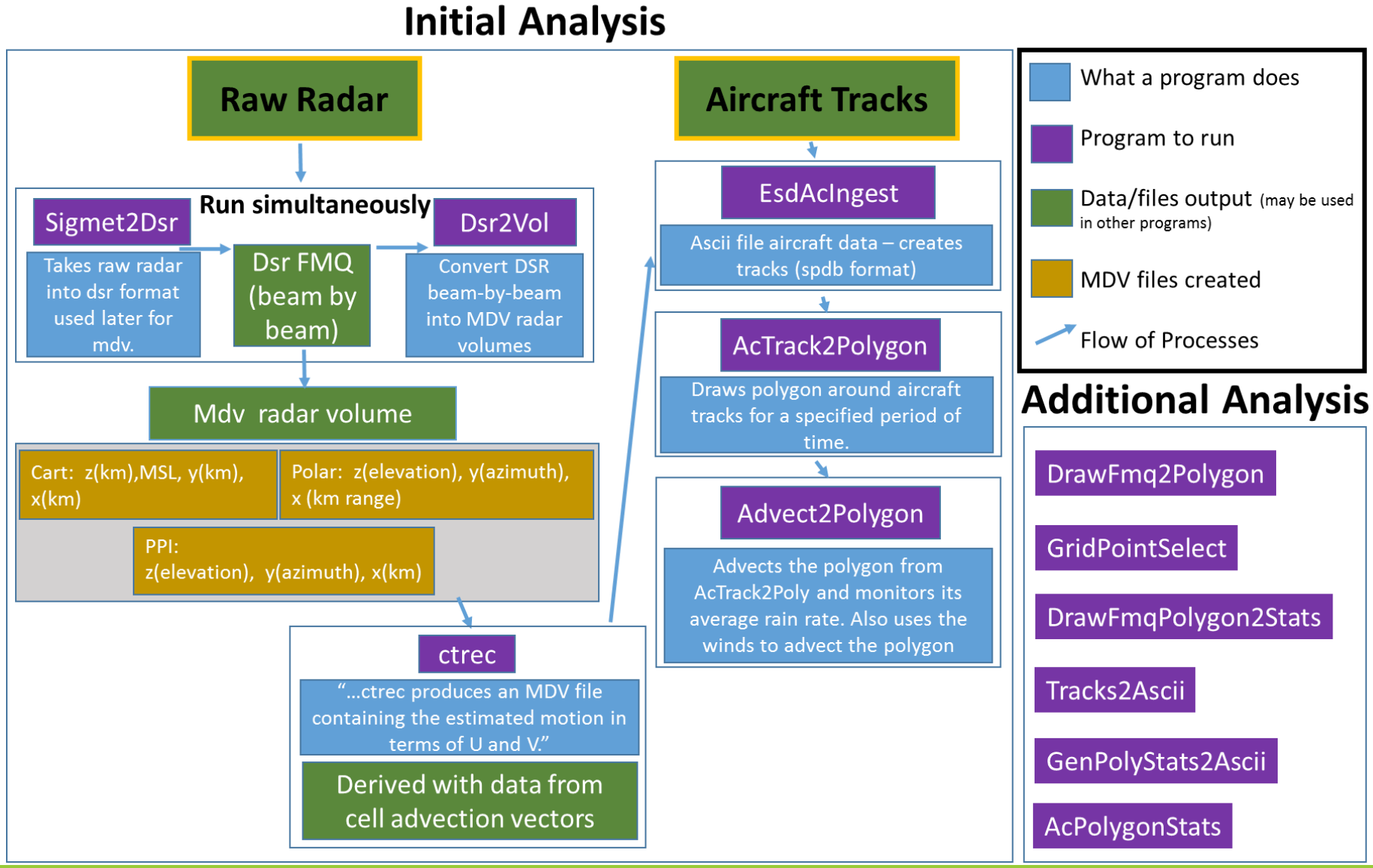


Average = 1330 #/cm^3



Average = 1630 m

TITAN Scripts for Analysis of the POLCAST Field Projects



Analysis of POLCAST with TITAN:

Calculate rain rate using Reflectivity

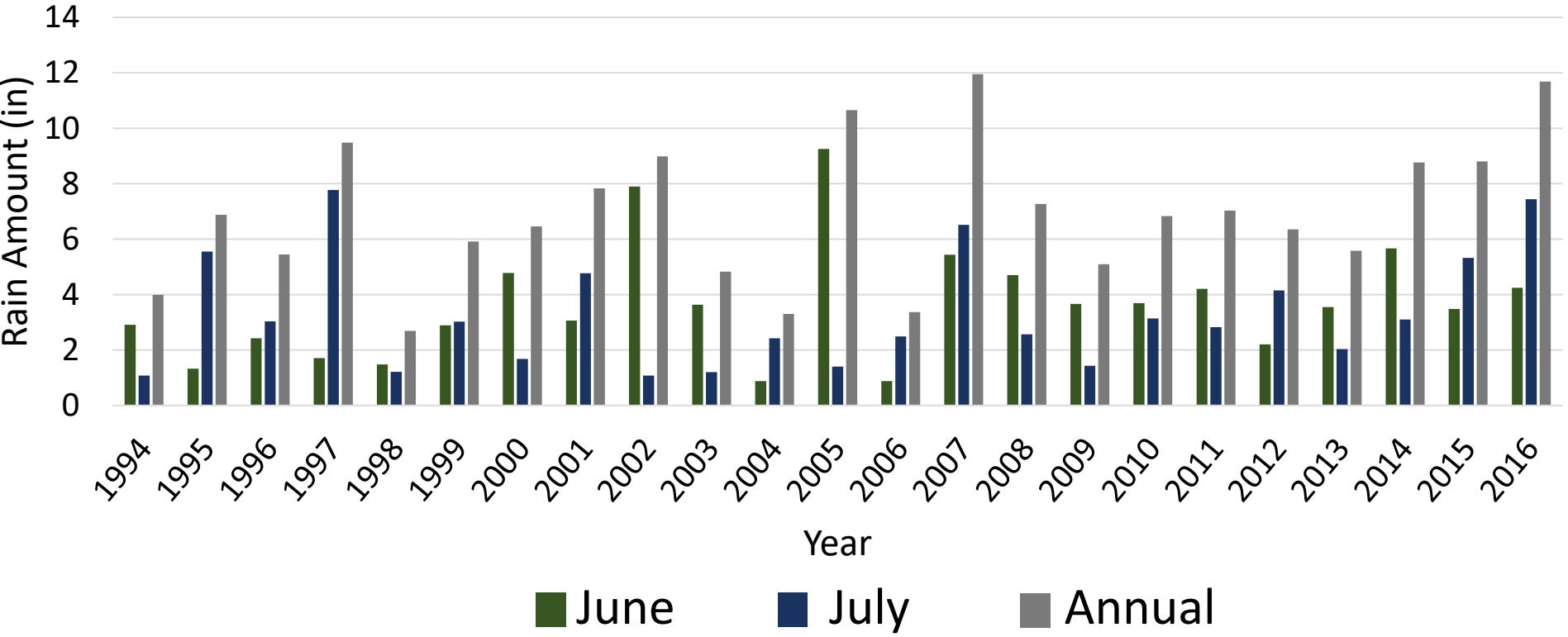
Z-R Relationship Equation used for Summer Deep Convection

$$Z = 300 * R^{1.4}$$

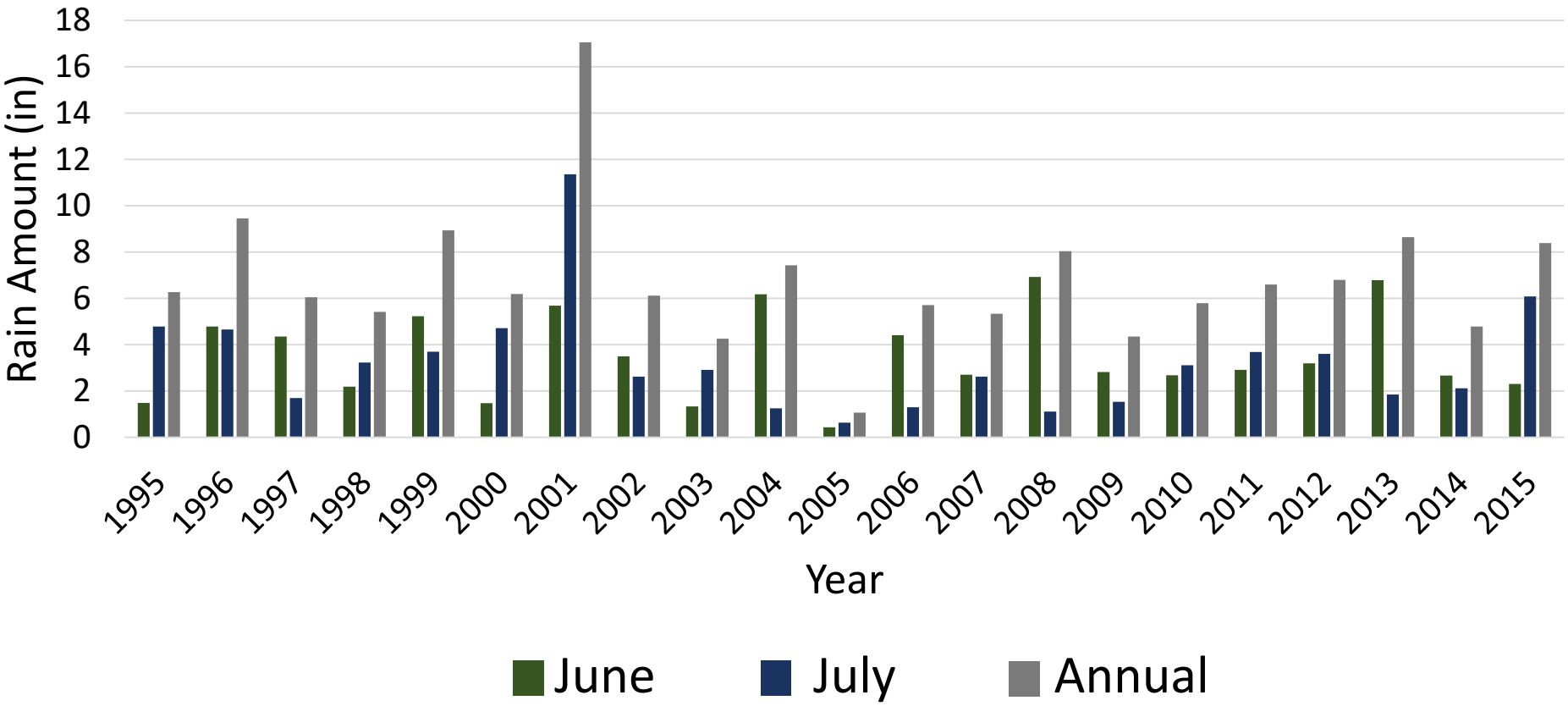
Z = reflectivity (mm^6/m^3)

R = Rain rate in mm/hr

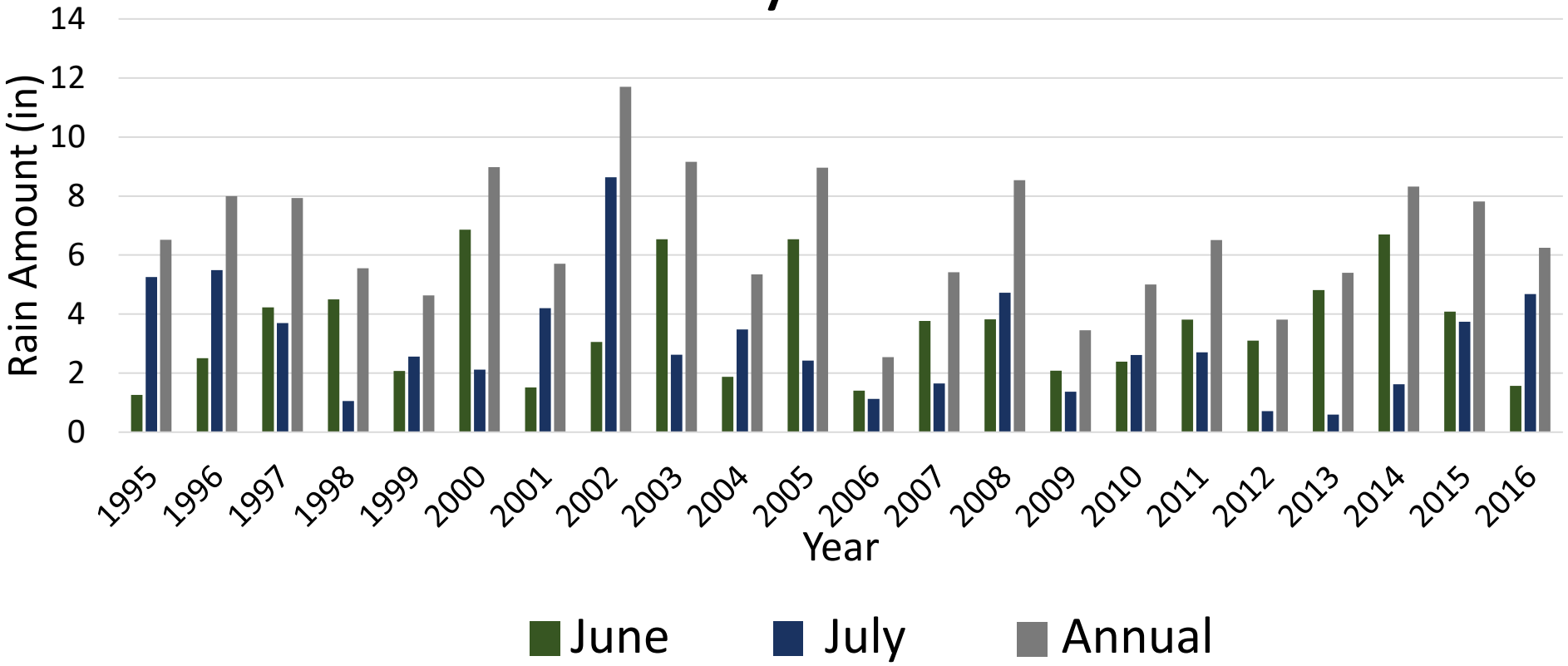
Cavalier


Rain Amount (in)
14
12
10
8
6
4
2
0
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
Year
June
July
Annual

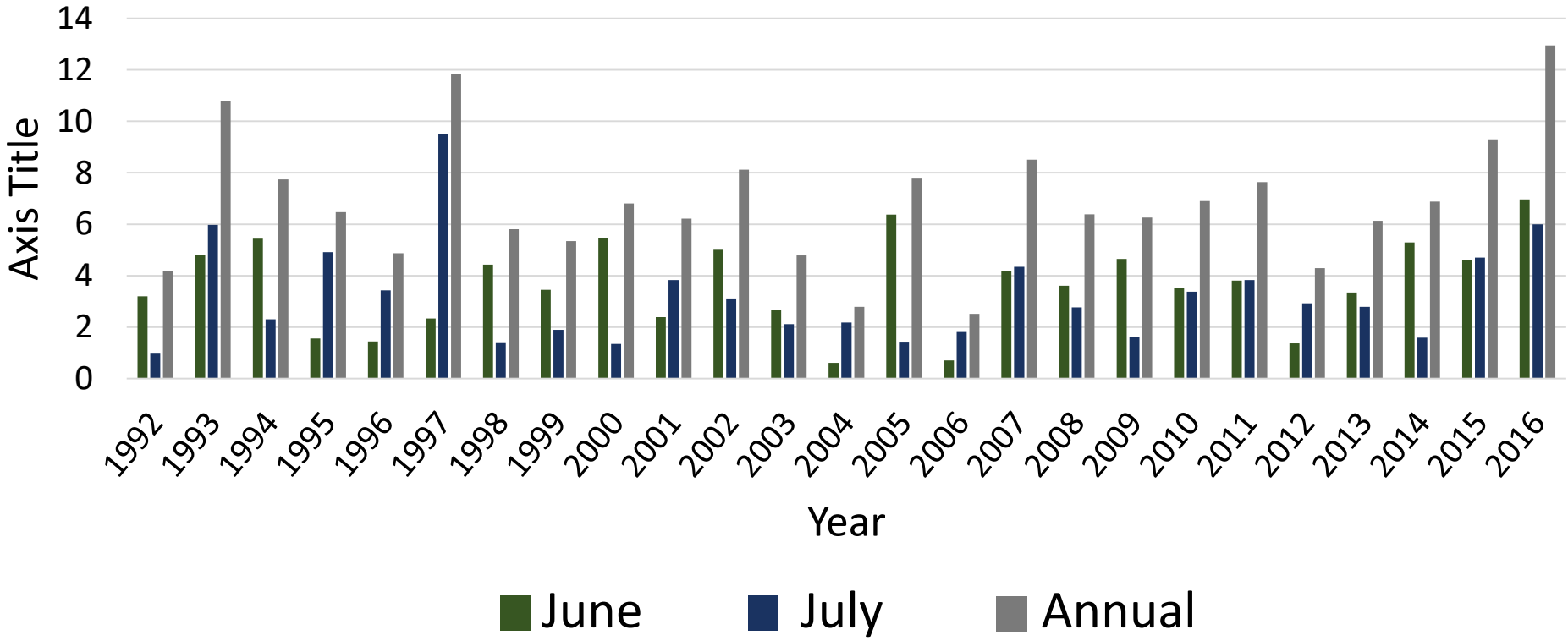
Eldred


Rain Amount (in)
18
16
14
12
10
8
6
4
2
0
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
Year
June
July
Annual

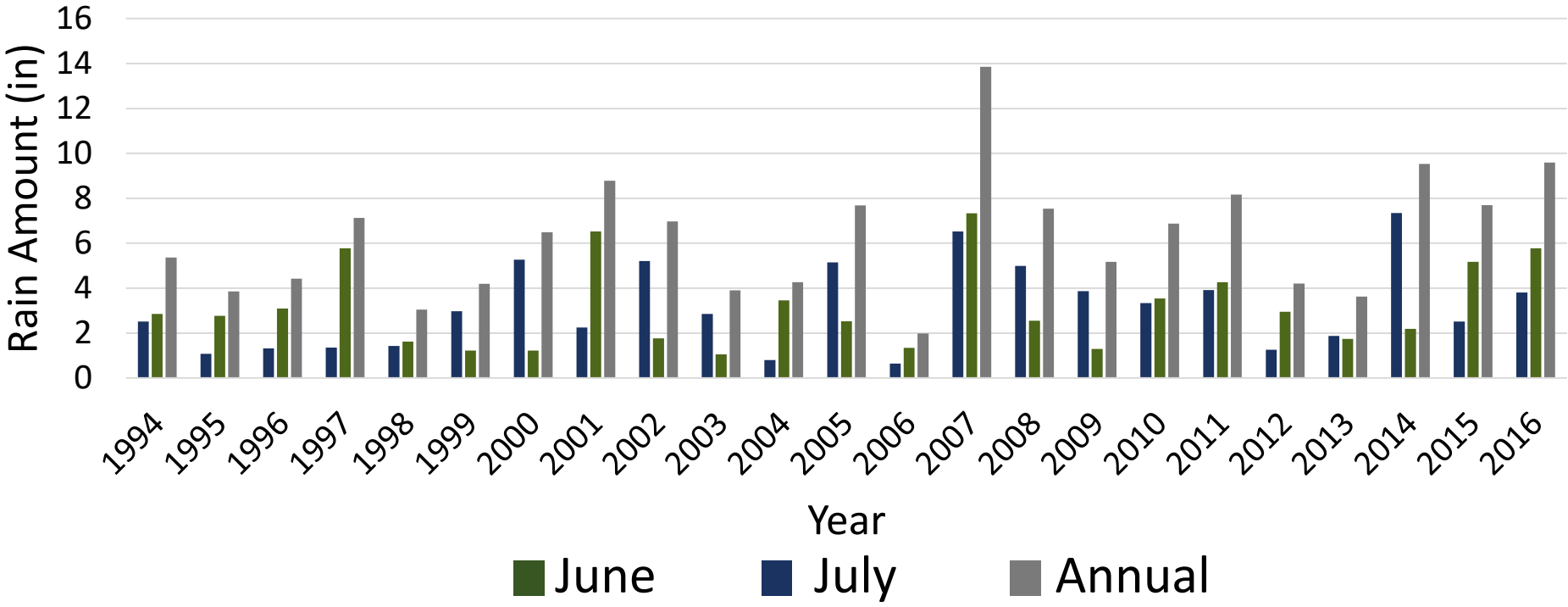
Mayville


14
12
10
8
6
4
2
0
Rain Amount (in)
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
Year
June
July
Annual

Forest River



St. Thomas


Rain Amount (in)
16
14
12
10
8
6
4
2
0
1994
1995
1996
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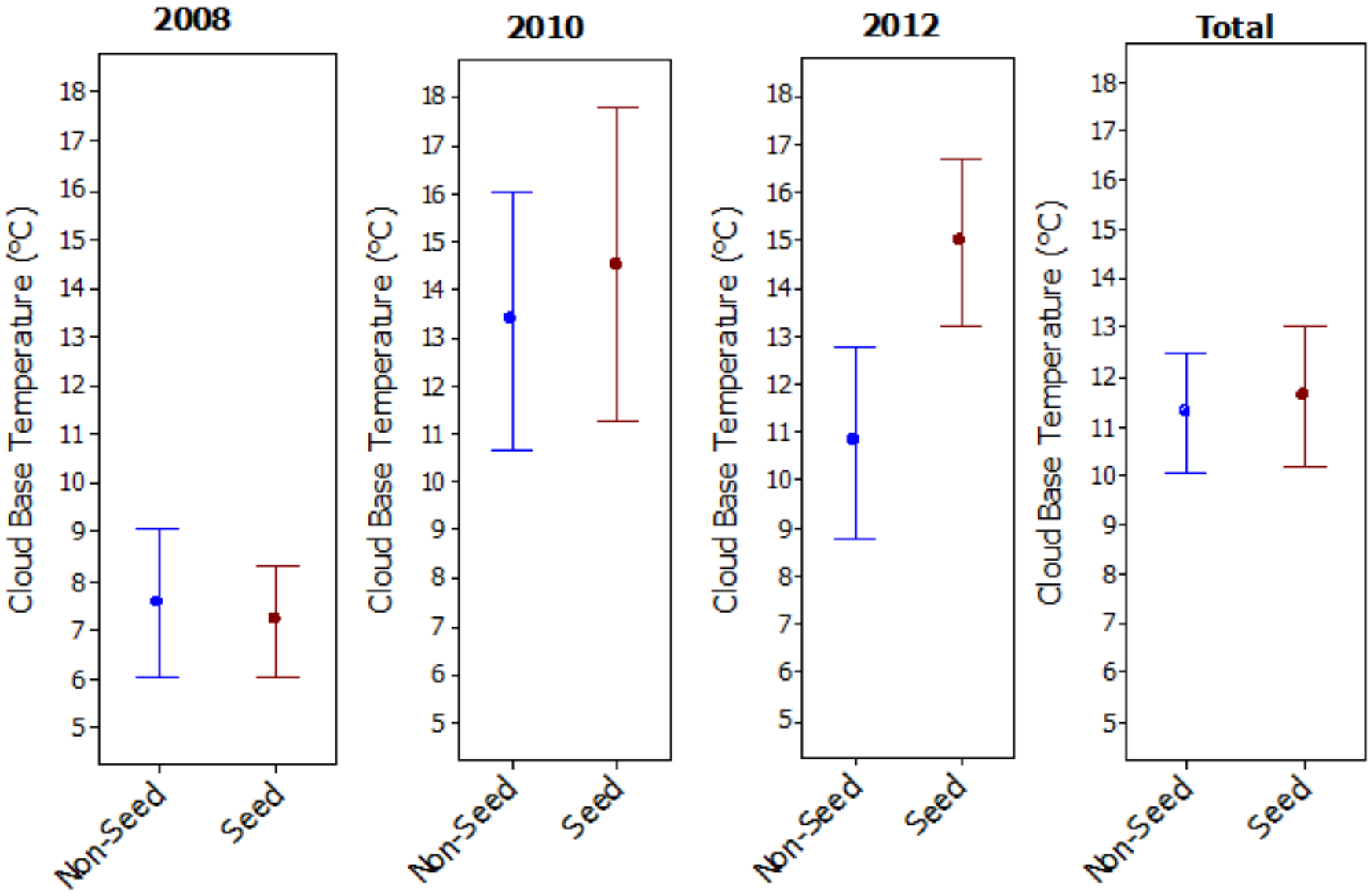
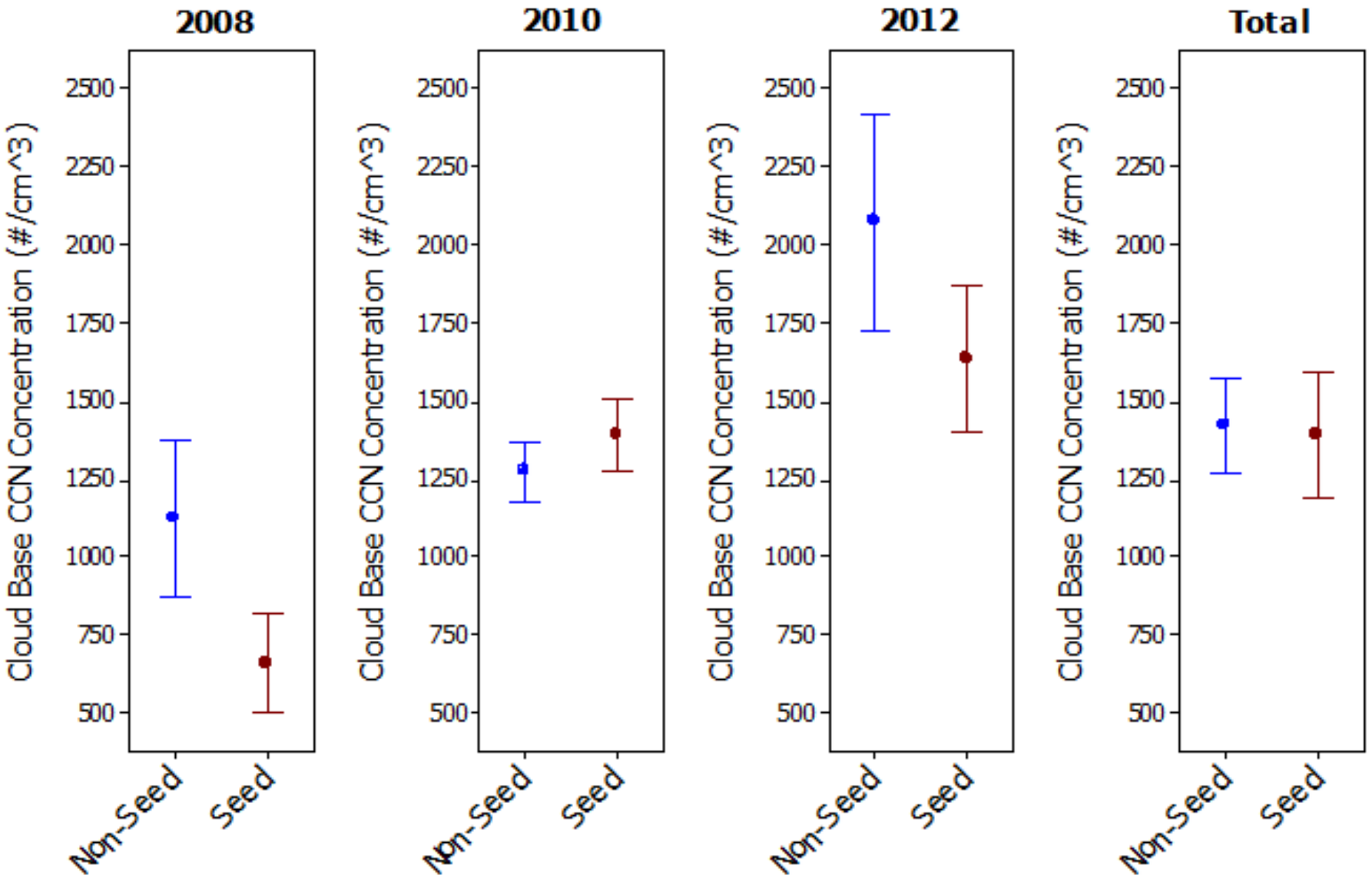
2014
2015
2016
Year
June
July
Annual

Cloud Base Temperature



Cloud Base CCN



Cloud Base Altitude