Precipitation Evaluation of the North Dakota Cloud Modification Project (NDCMP) Using Rain Gauge Observations

Matthew Tuftedal

M.S. Thesis Defense, University of North Dakota

09 July 2019

Committee Members:

Dr. David Delene*, UND

Dr. Andrew Detwiler, UND

Dr. Aaron Kennedy, UND

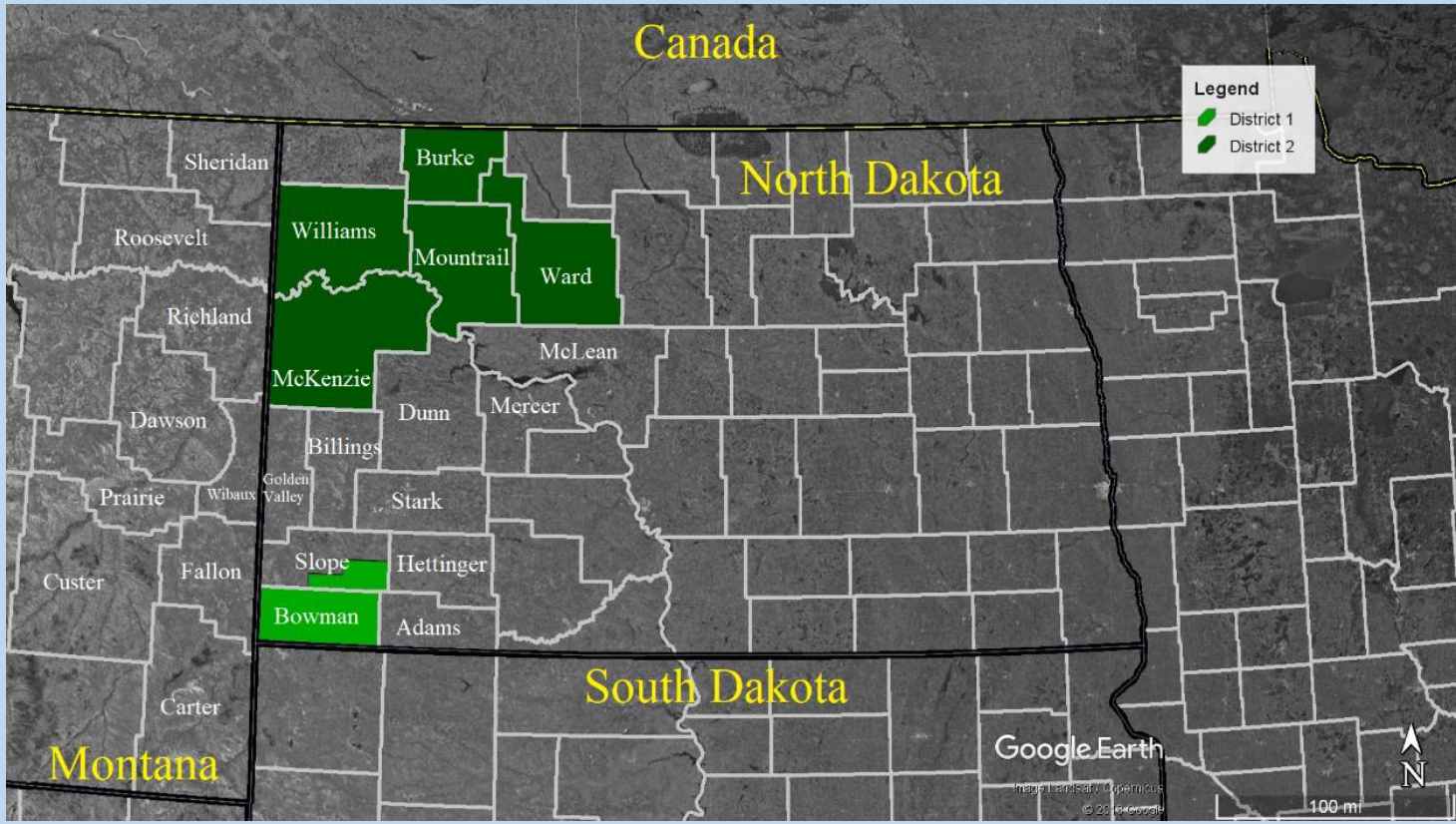
*Committee Chair

Motivation and Objective

- The North Dakota Cloud Modification Project (NDCMP) costs the state of North Dakota approx. $1.0 million per year or approx. 13 cents per acre (NDMP 2018).
- The last study performed on the NDCMP was conducted in 2005 (Wise 2005).
- Analyzing the effectiveness of the NDCMP can help future economic cost/benefit ratio studies and are important so sponsors and the public are well informed.
- Determining the effectiveness of the NDCMP at increasing rainfall within the project area.

Project Background

- The NDCMP has ran a non-randomized cloud seeding operation in ND since 1976.
  - (Schneider and Langerud 2011)
- Primary goal of the program is hail suppression to reduce crop loss, but precipitation enhancement was quickly added.
- Operations are conducted in two districts during June, July, August and occasionally early September.
  - (NDARB 2018)



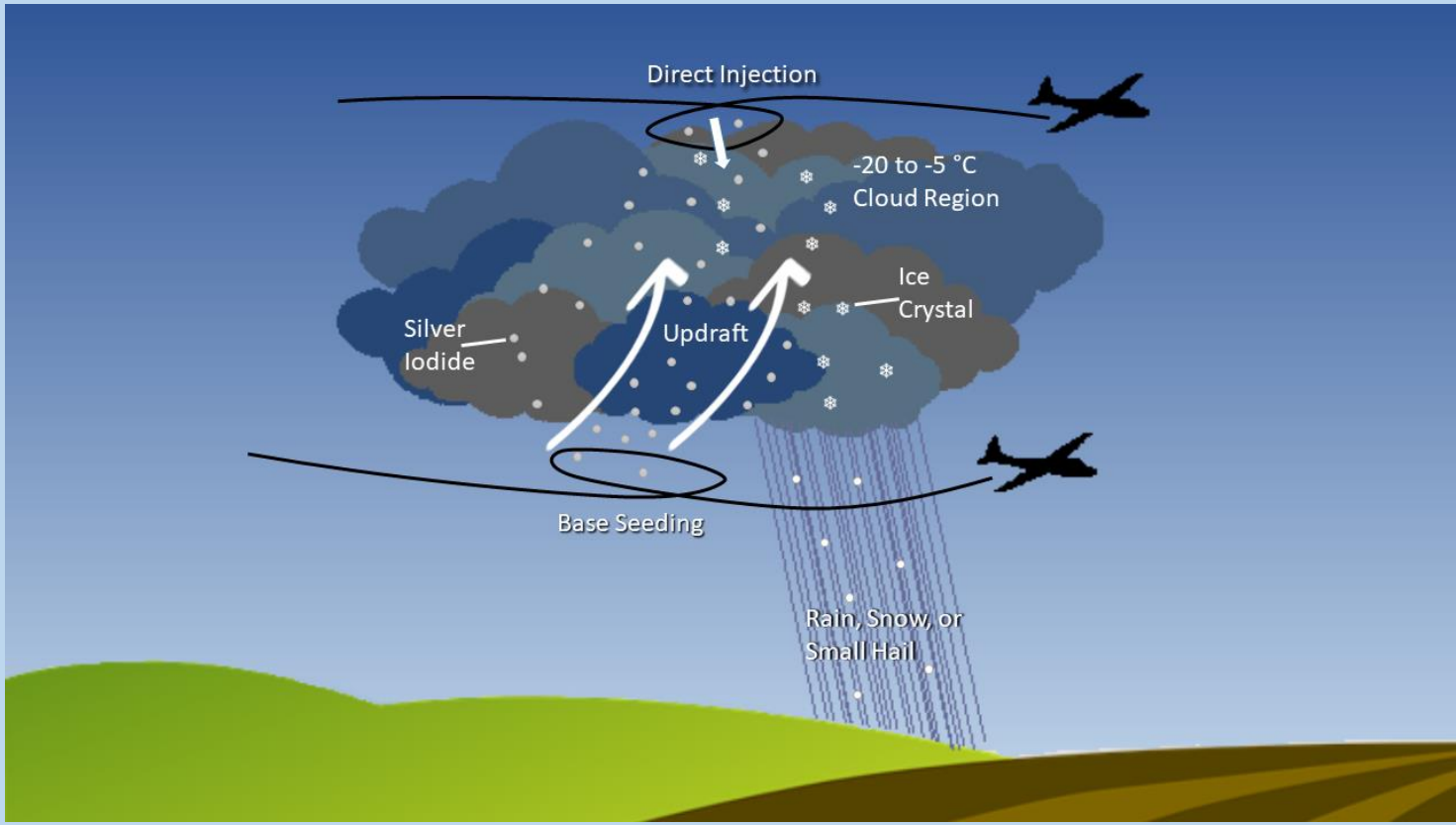
Radar and Aircraft

- Two C-Band Radars are located in Bowman and Stanley, ND.
- Eight aircrafts have been used in recent years, with planes located in Bowman, McKenzie, Williams, Mountrail and Ward County.
- Source: (NDARB 2018)

Photo Credit: NDCMP

Cloud Seeding

- Seeding agents are released at cloud base and direct injection at the cloud top.
- Cloud base seeding uses wing-mounted ice nucleus generators and burn-in-place flares.
- Direct injection uses ejectable flares and dry ice.



- Source: (NDARB 2014; Delene 2016)

Previous Evaluations of the NDCMP

- By using National Weather Service (NWS) Cooperative Observer Program (COOP) rain gauges, Smith et al. (2004) studied whether a cloud seeding effect was present.
- A target/control methodology consisting of 11 stations in the NDCMP target area and 25 stations in eastern Montana as the control was used.
- Results showed little to no increase in rainfall in this analysis and a p-value of 0.32.

Previous Evaluations of the NDCMP

- Wise (2005) analyzed the effects of the NDCMP using a target, downwind and control approach.
- The control/downwind region was determined by daily storm motion from 1999 to 2002.
- North Dakota Atmospheric Resource Board Cooperative Observer Network (NDARBCON) rain gauges were used for 1977 to 2003.
- Results found an increase in rainfall of at least 5 % in four out of seven cases.
  - Of those four, only two were determined statistically significant ($p\text{-value} < 0.05$)

NDARBCON Data

- NDARBCON uses a “Tru-Chek” wedge-shaped rain gauge.
- NDARBCON rain gauges measure rainfall to the nearest hundredth of an inch.
- Rainfall measurements are taken at 0800 AM everyday.
- The observational period for the NDARBCON observers is April 1st through September 30th each year.

NWS COOP Data

- NWS COOP observers are supplied with an 8-inch rain gauge.
- The 8-inch gauge is a simple non recording gauge consisting of four parts:
  - Measuring stick
  - Measuring tube
  - Collector funnel
  - Overflow can
- Rainfall can be measured within a tenth of an inch and can hold 20 inches of rainfall.
- Source: (NWS 1999)

Data

- Langerud and Gilstad (2003) compared NDARBCON and NWS COOP gauges over a 23-year period from 1977-1999.
- Rain gauges were compared multi-annually and annually.
- Results showed rainfall totals within approx. a half an inch per year and a correlation of 0.998.

Project Evaluation

- The rainfall in this study was evaluated by using a target and control analysis.
- Target and control method provides a statistical analysis of the rainfall and not a physical process evaluation.
- A target is an area where something is being applied.
- A control is an area where conditions are left untreated or untouched.

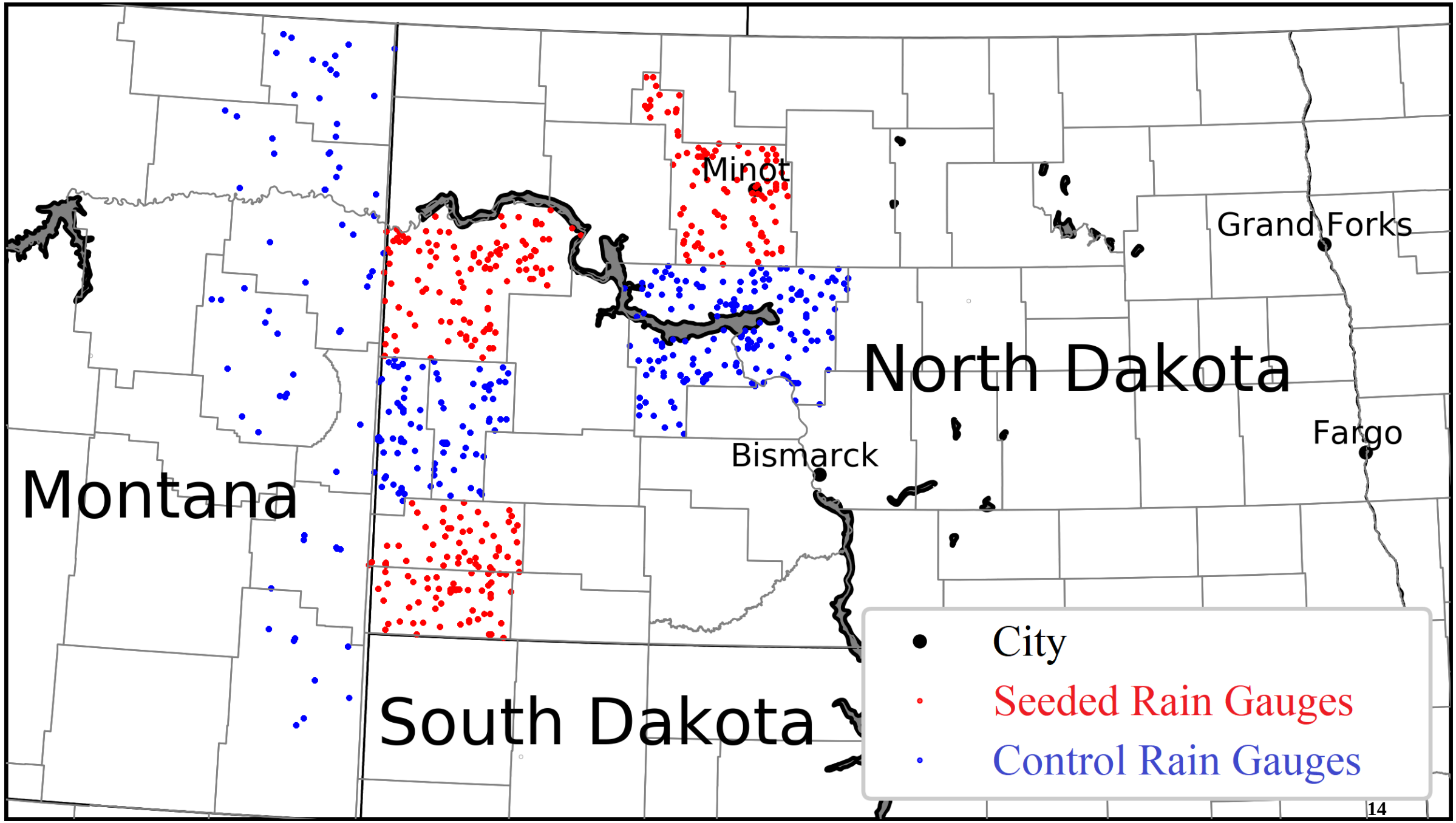
Target Region

- The target regions are determined by the years active in the NDCMP.
- Of those counties, Bowman, Slope, McKenzie, and Ward Counties were selected.

Counties	District	Years Participated	Total Years
Adams	1	1977-1980	3
Bowman	1	1977-2018	41
Hettinger	1	1977-1988	11
Slope	1	1977-1998, 1999-2018	41
Burke	2	2015-2018	3
McKenzie	2	1977-2018	41
McLean	2	1977-1984	7
Mountrail	2	1977-2018	41
Ward	2	1977-2018	41
Williams	2	1997-2018	21

Control Region

- Controls were designated as counties that have not participated in the NDCMP or only participated in a relatively short period.
- However, selecting a control area that may not be affected by downwind effects proved to be difficult.
- DeFelice et al. (2014) found that downwind effects from cloud seeding increases rainfall by 5 – 15 %, and Wise (2005) found a 13% increase in downwind rainfall within the NDCMP.


Minot
Grand Forks
North Dakota
Fargo
Bismarck
Montana
South Dakota
City
Seeded Rain Gauges
Control Rain Gauges

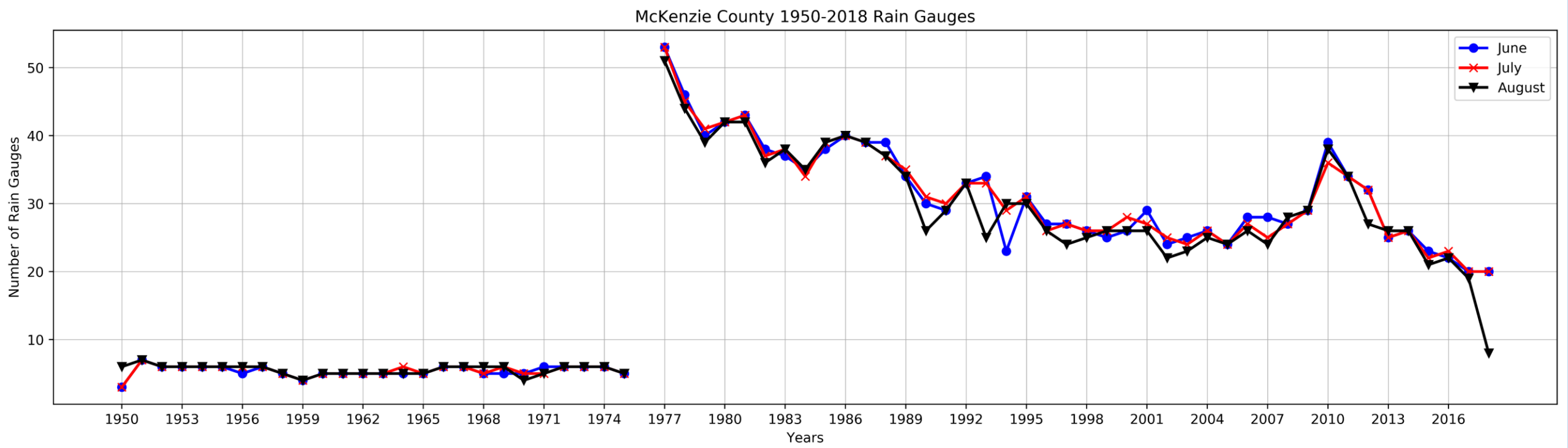
Climatology Data

- NWS COOP rain gauges were available within all target/control locations in both ND and MT dating back to before 1950.
- This provided enough data to perform a target/control analysis for 1950-1975 and 1977-2018.
- The amount of rainfall for 1950-1975 may not be representative of current climate in western ND, however the amount is not essential for this study.
- It is assumed that ratios calculated for this period were representative of ratios during the study period without the effects of seeding.

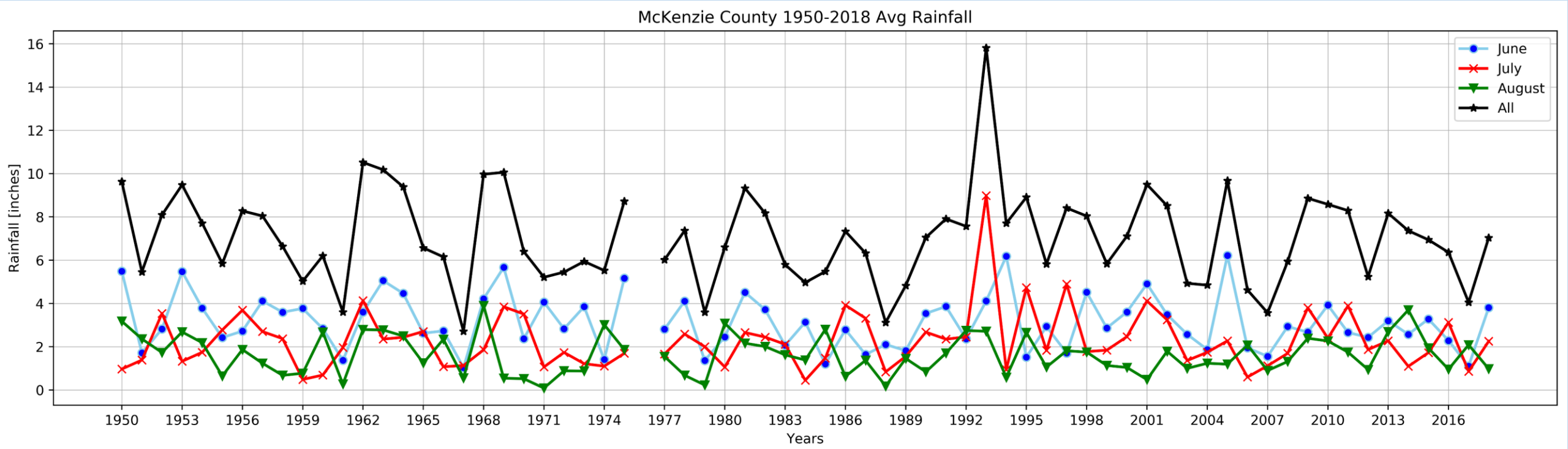
Missing Data

- Despite having vast amounts of rain gauges available throughout the history of the NDCMP, time consistency (e.g. year-to-year reporting) of rain gauge observations were an issue.
- To handle missing data for the NDARBCON gauges, gauges were checked to see if a complete record for June, July, or August were available.
- If a gauge had a complete record for at least one of the months, it was used towards the calculation of monthly total rainfall for the year.

McKenzie County Rain Gauges 1950-2018



McKenzie County Rain Fall 1950-2018



Rainfall Evaluation

- Precipitation amounts for each target and control region were calculated for the full study period (1977-2018) and for the pre-NDCMP period (1950-1975).
- All gauge data within each target and control region were combined to obtain a monthly rainfall amount.

Monthly Rainfall for a Single Station

$$R_{station} = \sum_{i=1}^{n_{days}} r_g(i)$$

- $R_{station}$ = the calculated monthly rainfall for a given station
- r_g = the rainfall amount recorded on a given day by the rain gauge
- n_{days} = the number of days in the given month

Monthly Rainfall for an Area

$$R_{monthly} = \sum_{i=1}^{n_{stations}} R_{station}(i)$$

- $R_{monthly}$ = the total monthly rainfall
- $R_{station}$ = the calculated monthly rainfall for a given station
- $n_{station}$ = the number of stations in the given month

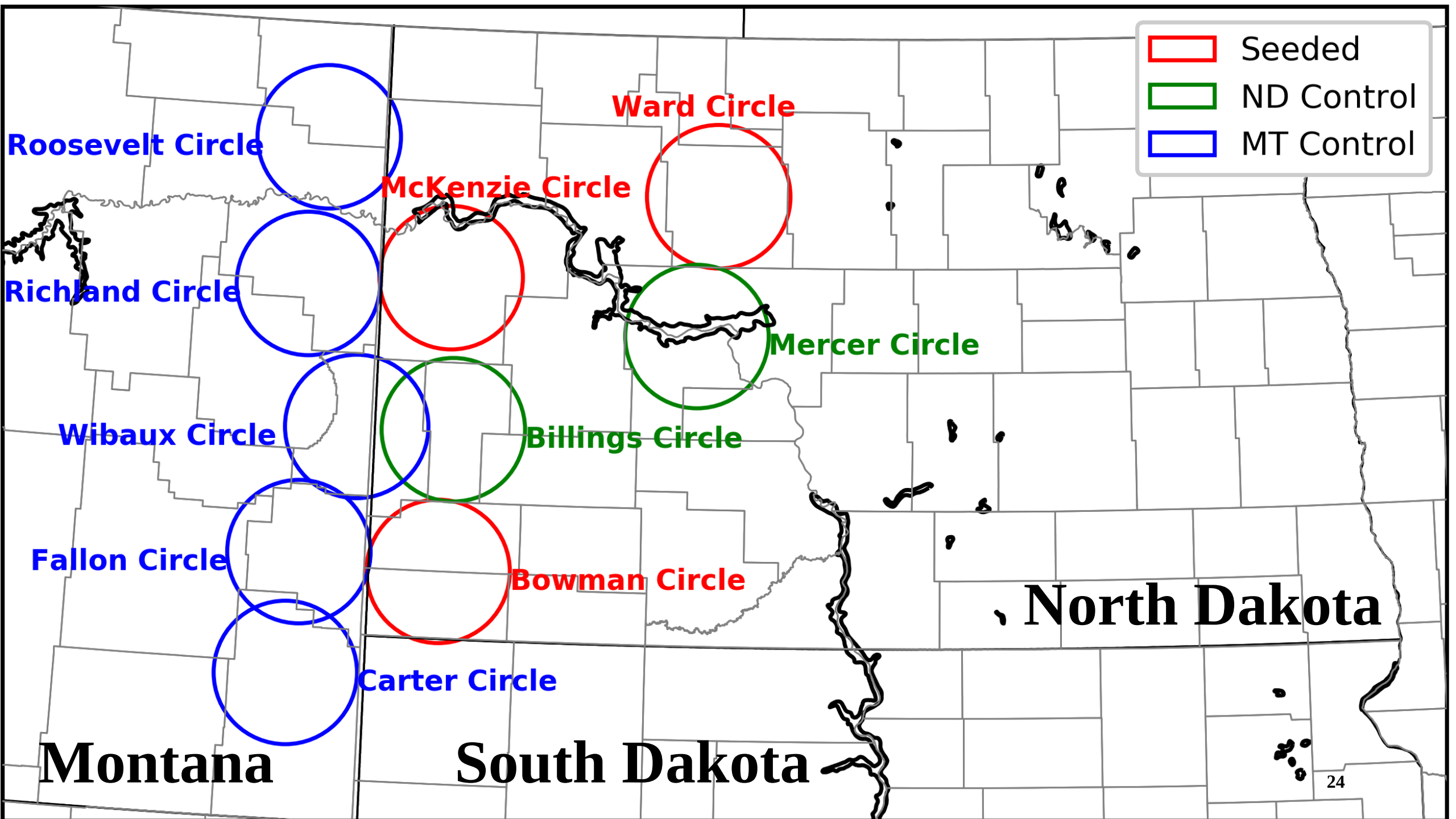
Seasonal Rainfall

$$R_{seasonal} = \sum_{i=1}^{n_{months}} \bar{R}_{monthly}(i)$$

- $R_{seasonal}$ = the sum of the average monthly rainfall
- $R_{monthly}$ = the calculated average monthly rainfall for June, July and August
- n_{months} = the number of months in the season

County Circles Method

- This was done to create specific areas to analyze and a way to weight the rain gauge data to a specific point within that circle.
- Circles with radii of 40 km, centered on a given point for each county are overlaid on the target and control region.
- The radius of 40 km was chosen to avoid overlap between target and control areas and to keep rain gauge observations to a centralized location within the county, but also to encompass as many rain gauges as possible.


Seeded
ND Control
MT Control
Ward Circle
Roosevelt Circle
McKenzie Circle
Richland Circle
Mercer Circle
Wibaux Circle
Billings Circle
Fallon Circle
Bowman Circle
Carter Circle
North Dakota
Montana
South Dakota

County Circles

$$w = \frac{R^2 - d^2}{R^2 + d^2}$$

- w = Weight of rain gauge to central location
- R = Radius of influence (40 km)
- d = Distance of the gauge from grid point
- Reference: Wise 2005

County Circles Weighted Rainfall

$$f_d = \sum_{i=1}^{n} w(i) * f_o(i)$$

- f_d = Calculated rainfall at grid point
- f_o = Monthly rainfall for a given station
- w = Weight of the given rain gauge
- n = Number of gauges within radius of influence
- Reference: Wise 2005

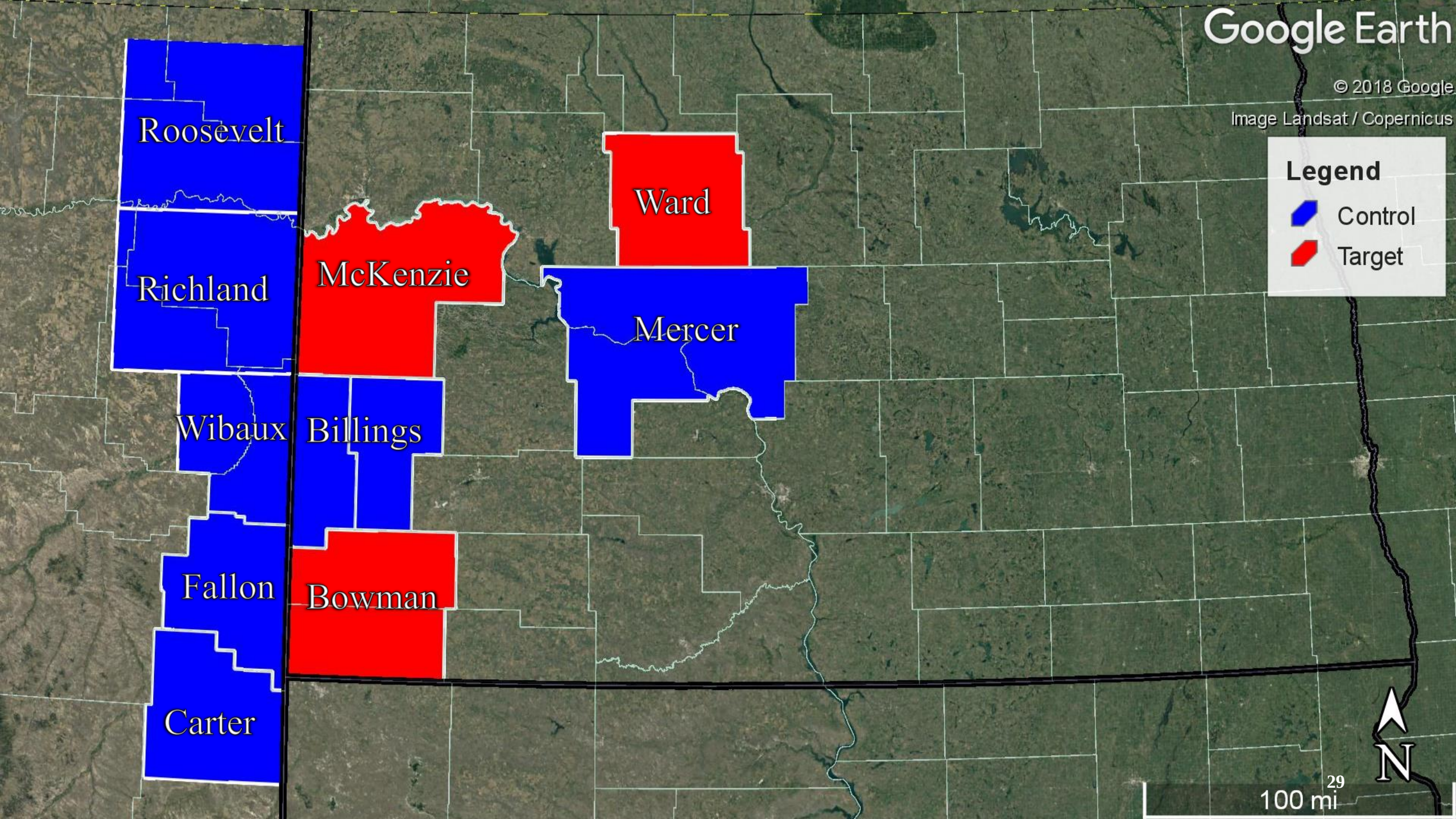
County Circles Monthly Weighted Rainfall

$$f_{d\ normalized} = \frac{f_d}{\sum_{i=1}^{n} w(i)_{year}}$$

- $f_{d\ normalized}$ = Monthly average rainfall averaged by the sum of the weights at a central point
- f_d = Calculated rainfall at grid point
- w = Sum of the weights
- n = Number of gauges within radius of influence

County Based Method

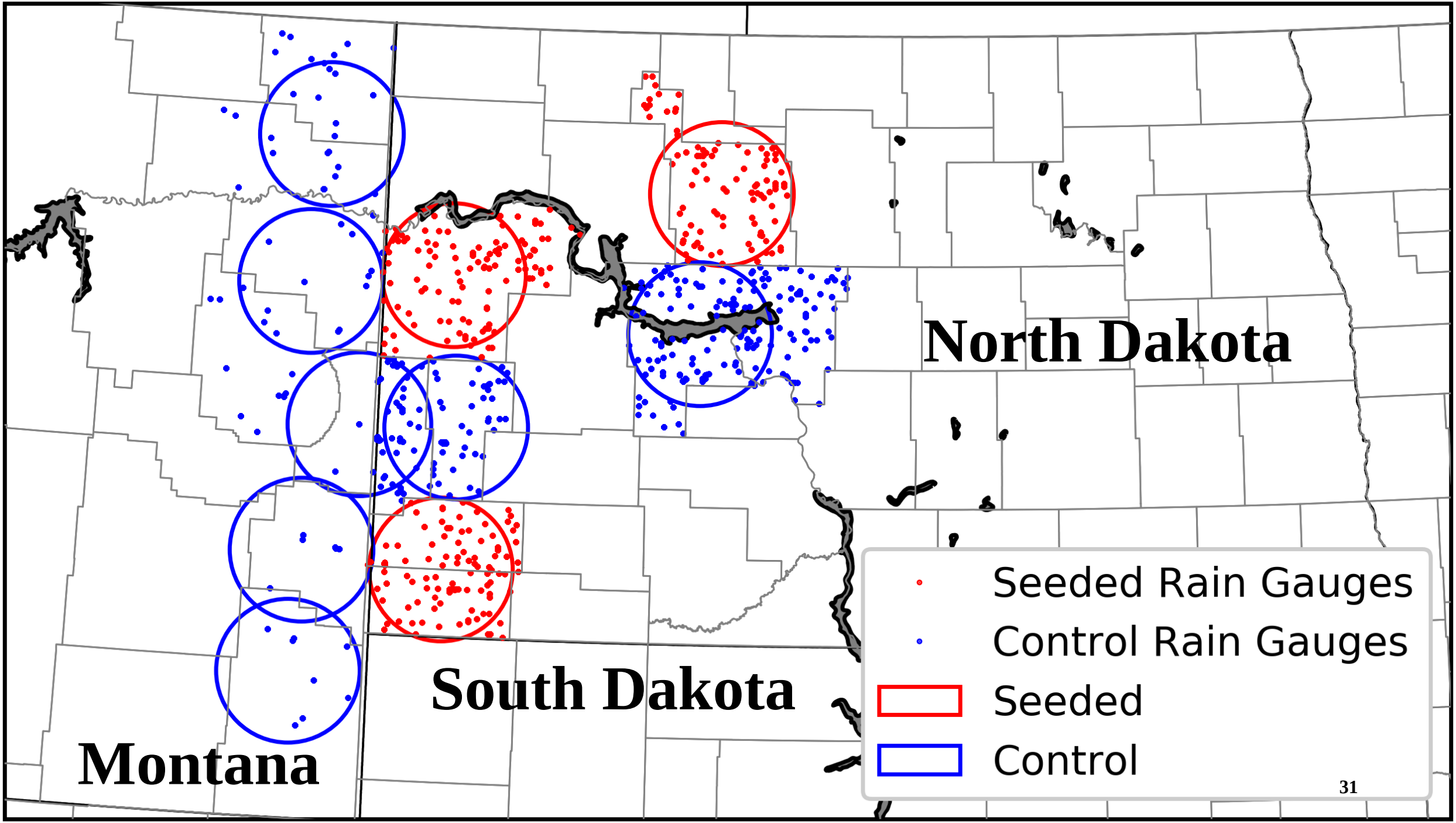
- To account for all possible rain gauges within a county, a county-based evaluation of rain gauges were done.
- Some counties were combined to create a larger county area than were within the given political county borders.
- The inclusion of more rain gauges could provide a better insight into the observed average rainfall over the entire county.
- Using the circle-based method may remove any visible effects seen on the outer edges of the circle.


Google Earth
© 2018 Google
Image Landsat / Copernicus
Legend
Control
Target
Roosevelt
Richland
McKenzie
Ward
Mercer
Wibaux
Billings
Fallon
Bowman
Carter
N
100 mi

County Based Monthly Rainfall

$$\bar{R}_{monthly} = \frac{\sum_{i=1}^{n_{stations}} R_{station}(i)}{n_{stations}}$$

- $\bar{R}_{monthly}$ = the average monthly rainfall for the entire county
- $R_{station}$ = the monthly rainfall for each station
- $n_{stations}$ = the number of rain gauges within the county for the given month


North Dakota
South Dakota
Montana
Seeded Rain Gauges
Control Rain Gauges
Seeded
Control

Statistical Methods

- To analyze the target and control rainfall differences, the following statistical methods were used:
  - Single ratio
  - Double Ratio
  - Single and Multiple Linear Regression

Single Ratio

- Once the rainfall for a given evaluation was completed, a single ratio between target and control were calculated for the pre-NDCMP and NDCMP periods.
- Each target was assigned to different control areas based on the proximity of their location.
- McKenzie was paired with:
  - Richland, Roosevelt, Wibaux, and Billings
- Bowman was paired with:
  - Carter, Fallon, Wibaux and Billings

Single Ratio

$$SR = \frac{\sum_{n=1}^{(years)} f_d^{June,July,August,and\ all}(seeded\ circle)}{\sum_{n=1}^{(years)} f_d^{June,July,August,and\ all}(control\ circle)}$$

- SR = a single ratio from the sum of the target and control ratios
- f_d = the weighted average or county-based average rainfall
- years = either 1950-1975 or 1977 to 2018

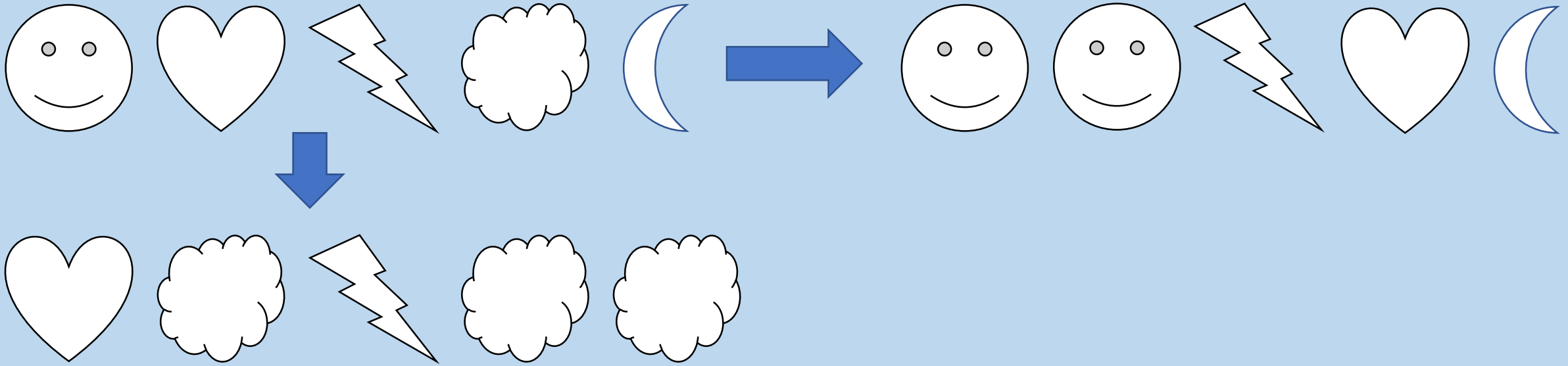
Double Ratio

$$DR = \frac{\sum_{n=1}^{1977-2018} f_d^{June,July,August,and\ all}(seeded\ circle)}{\sum_{n=1}^{1977-2018} f_d^{June,July,August,and\ all}(control\ circle)} \Big/ \frac{\sum_{n=1}^{1950-1975} f_d^{June,July,August,and\ all}(seeded\ circle)}{\sum_{n=1}^{1950-1975} f_d^{June,July,August,and\ all}(control\ circle)}$$

- DR = a single value calculated from the single ratios from NDCMP and pre-NDCMP time periods

Bootstrapping

- Bootstrapping randomly resamples data to create a new data set from observed data.



- Sampling with replacement was used in this study.

Bootstrapping

- A Bootstrapping method was used in two different ways in this study.
  - The first way was to examine the natural variation of the single and double ratios.
  - The second way was to determine how many rain gauges were needed to get an adequate measurement in rainfall.

1950 - 1975 Single Ratios

County Pair (Target/Control)	June	July	August	Seasonal
McKenzie/Billings	0.84	0.95	0.92	0.89
McKenzie/Richland	1.13	1.06	1.04	1.09
McKenzie/Wibaux	0.88	0.98	0.96	0.92
McKenzie/Roosevelt	1.21	1.09	1.02	1.12
Bowman/Billings	0.89	0.96	0.84	0.90
Bowman/Wibaux	0.93	0.99	0.88	0.94
Bowman/Carter	0.94	0.95	1.01	0.96
Bowman/Fallon	1.20	1.20	1.25	1.21
Ward/Mercer	0.99	0.96	1.04	0.99
Average	1.00	1.02	1.00	1.00
Standard Deviation	0.14	0.09	0.12	0.11

1977 - 2018 Single Ratios

County Pair (Target/Control)	June	July	August	Seasonal
McKenzie/Billings	1.00	1.03	0.89	0.98
McKenzie/Richland	1.17	1.12	1.17	1.15
McKenzie/Wibaux	1.05	1.09	0.94	1.03
McKenzie/Roosevelt	1.12	1.06	1.20	1.12
Bowman/Billings	1.01	0.89	0.88	0.94
Bowman/Wibaux	1.06	0.94	0.93	0.99
Bowman/Carter	0.91	0.96	0.88	0.92
Bowman/Fallon	1.19	1.28	1.23	1.23
Ward/Mercer	1.01	0.93	0.93	0.96
Average	1.06	1.03	1.01	1.04
Standard Deviation	0.09	0.12	0.15	0.11

Double Ratios

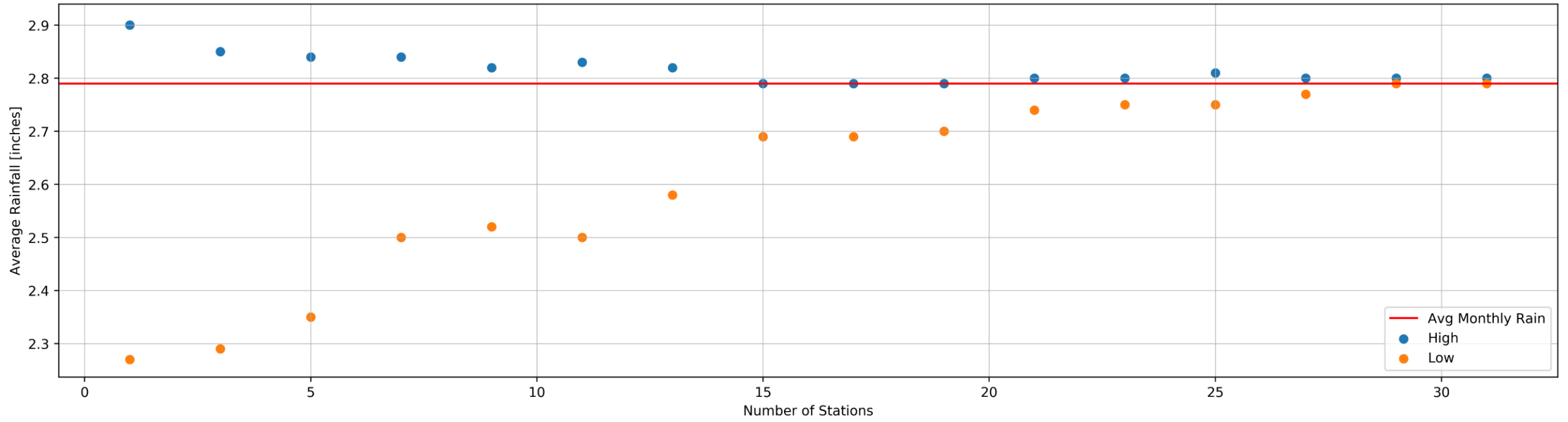
County Pair (Target/Control)	June	July	August	Seasonal
McKenzie/Billings	1.19	1.08	0.97	1.10
McKenzie/Richland	1.04	1.06	1.13	1.06
McKenzie/Wibaux	1.19	1.24	0.96	1.12
McKenzie/Roosevelt	0.93	0.97	1.18	1.00
Bowman/Billings	1.13	0.93	1.05	1.04
Bowman/Wibaux	1.14	0.95	1.06	1.05
Bowman/Carter	0.97	1.01	0.87	0.96
Bowman/Fallon	0.99	1.07	0.98	1.02
Ward/Mercer	1.02	0.97	0.89	0.97
Average	1.07	1.03	1.01	1.04
Standard Deviation	0.10	0.10	0.10	0.05

Bootstrapped Double Ratios

County Pair (Target/Control)	Observed Seasonal Double Ratio	95 % confidence interval	P-value
McKenzie/Billings	**1.10**	**0.99-1.22**	**0.07**
McKenzie/Richland	1.06	0.98-1.15	0.14
McKenzie/Wibaux	**1.12**	**1.00-1.23**	**0.03**
McKenzie/Roosevelt	1.00	0.90-1.10	0.93
Bowman/Billings	1.04	0.93-1.16	0.48
Bowman/Wibaux	1.05	0.94-1.17	0.35
Bowman/Carter	1.01	0.91-1.12	0.83
Bowman/Fallon	0.95	0.86-1.05	0.37
Ward/Mercer	0.96	0.87-1.07	0.54

Rain Gauges Needed

- Rain gauges from McKenzie and Billings County for June 1977 were used to determine the minimum number of rain gauges needed to measure the average rainfall within a tenth of an inch and one hundredth of an inch.
- 95% confidence intervals were constructed around the average monthly rainfall for a varying number of rain gauges to determine the uncertainty in rainfall.
- Each bootstrap sampled from the pool of 33 rain gauges 100,000 times.


Average Rainfall [inches]
2.9
2.8
2.7
2.6
2.5
2.4
2.3
0
5
10
15
20
25
30
Number of Stations
Avg Monthly Rain
High
Low

Conclusions

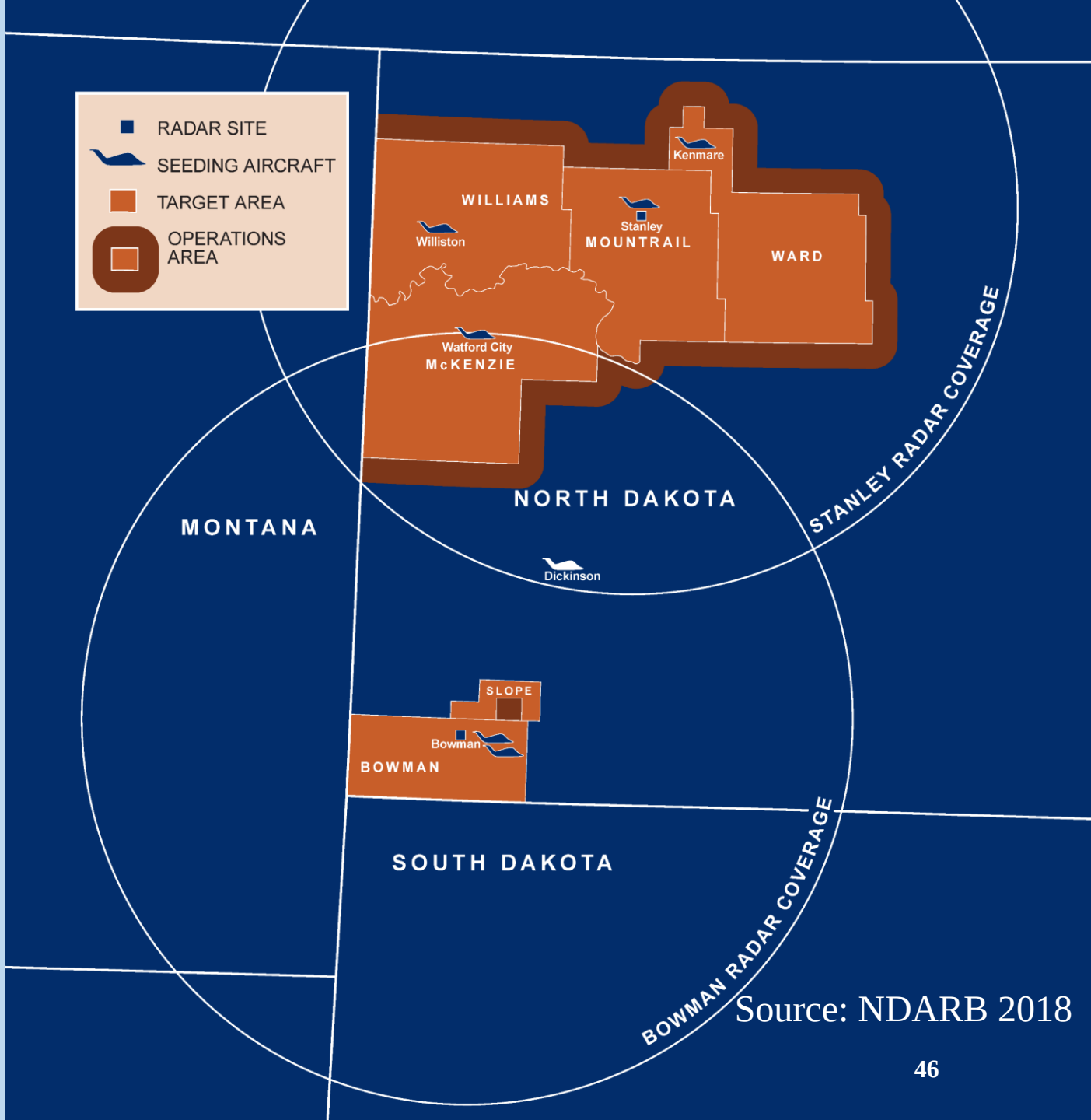
- To adequately sample rainfall, at least 15 rain gauges are needed in each county along with a proper spatial distribution of each rain gauge.
- Six out of the nine target regions in the County-Based Method received at least 2% or more rainfall than the control region in the double ratio calculations.
- The double ratio target/control pairs of McKenzie/Billings and McKenzie/Wibaux saw the largest increase of 10 to 12 % with p-values < 0.10.

Conclusions

- Results for the Single Linear Regression showed an increase of 1 - 12 % in McKenzie and Bowman in cases with a standard error < 6 %.
- Multiple Linear Regression showed an increase 3 - 7 % in cases with a standard error < 6 %.

Discussion

- Differences in increases between McKenzie and Bowman could be caused by a lack of a southern buffer zone on Bowman County.
- Depending on where storms are seeded, Bowman may not be large enough to see the full effect of the rainfall enhancement, where McKenzie can.
- Rainfall in Bowman may be affected by using rain gauges within Slope County that do not actively participate in the NDCMP, but previously have.
- Using 1950 -1975 as a pre-NDCMP period has limitations.



Source: NDARB 2018

Future Work

- Additional analysis needs to be conducted on the District I and II on differences in meteorology and project operations.
- Incorporate radar observation into the analysis.
- Analyzing the effects of cloud seeding in respect to wind direction, but using upwind controls, may provide a better target/control analysis than stationary controls.

Acknowledgements

- North Dakota Water Resources Research Institute
- Darin Langerud
- My Committee
- My Brother, Kris
- Chelsea Augustine
- My Mom
- Everyone here

References

- Bangsund, D. A., and F. L. Leistritz, 2009: *Economic Impacts of Cloud Seeding on Agricultural Crops in North Dakota*. North Dakota State University, Department of Agribusiness and Applied Economics, http://www.swc.nd.gov/arb/pdfs/SeedingEconImpact.pdf (Accessed January 28, 2016).
- DeFelice, T. P., J. Golden, D. Griffith, W. Woodley, D. Rosenfeld, D. Breed, M. Solak, and B. Boe, 2014: Extra area effects of cloud seeding — An updated assessment. *Atmospheric Research*, **135–136**, 193–203, https://doi.org/10.1016/j.atmosres.2013.08.014.
- Delene, D. J., 2016: Suitability of North Dakota For Conducting Effective Hygroscopic Seeding. *J. Wea. Modification*, **48**, 43–67.
- Johnson, H. L., 1985: *An Evaluation of the North Dakota Cloud Modification Project: 1976-1982*.
- NDARB, 2014: North Dakota Cloud Seeding Questions and Answers. *North Dakota Water Commission and State Engineer*,. http://www.swc.nd.gov/arb/ndcmp/pdfs/q_a.pdf (Accessed March 28, 2019).
- ____, 2018: *2018 Final Operations Report North Dakota Cloud Modification Project*. North Dakota Atmospheric Resource Board, http://www.swc.nd.gov/arb/ndcmp/pdfs/finalreport.pdf (Accessed January 15, 2019).
- Schaffner, L. W., J. E. Johnson, H. Vruegdenhill, and J. Enz, 1983: *Economic Effects of Added Growing Season Rainfall on North Dakota Agriculture*. Department of Agricultural Econmics, https://www.swc.nd.gov/arb/ndcmp/pdfs/EconEff_AddGrowRain_1983.pdf.
- Schneider, M. D., and D. Langerud, 2011: Operational Improvements on the North Dakota Cloud Modification Project. *Journal of Weather Modification*, **43**, 84–88.
- Smith, P. L., L. R. Johnson, D. L. Priegnitz, and J. Paul W Mielke, 1992: A Target-Control Analysis of Wheat Yield Data for the North Dakota Cloud Modification Project Region. *The Journal of Weather Modification*, **24**, 98–105.
- ____, ____, ____, B. Boe, and P. W. Mielke, Jr, 1997: An Exploratory Analysis of Crop Hail Insurance Data for Evidence of Cloud Seeding Effects in North Dakota. *J. Appl. Meteor.*, **36**, 463–473.
- ____, P. W. Mielke, Jr, and F. J. Kopp, 2004: *Exploratory Analysis of Climatic Raingage Data For Evidence of Effects of the North Dakota Cloud Modification Project on Rainfall in the Target Area*. North Dakota Atmospheric Resource Board, http://www.swc.nd.gov/arb/ndcmp/pdfs/ExplorAnalysisClimaticRainDataNDCMPEffects_2004.pdf.
- Wise, E., 2005: Precipitation evaluation of the North Dakota Cloud Modification Project (NDCMP). University of North Dakota, 63 pp.

Questions?

Extra Slides

Weiss (2005) Target/Control Based on Storm Flow

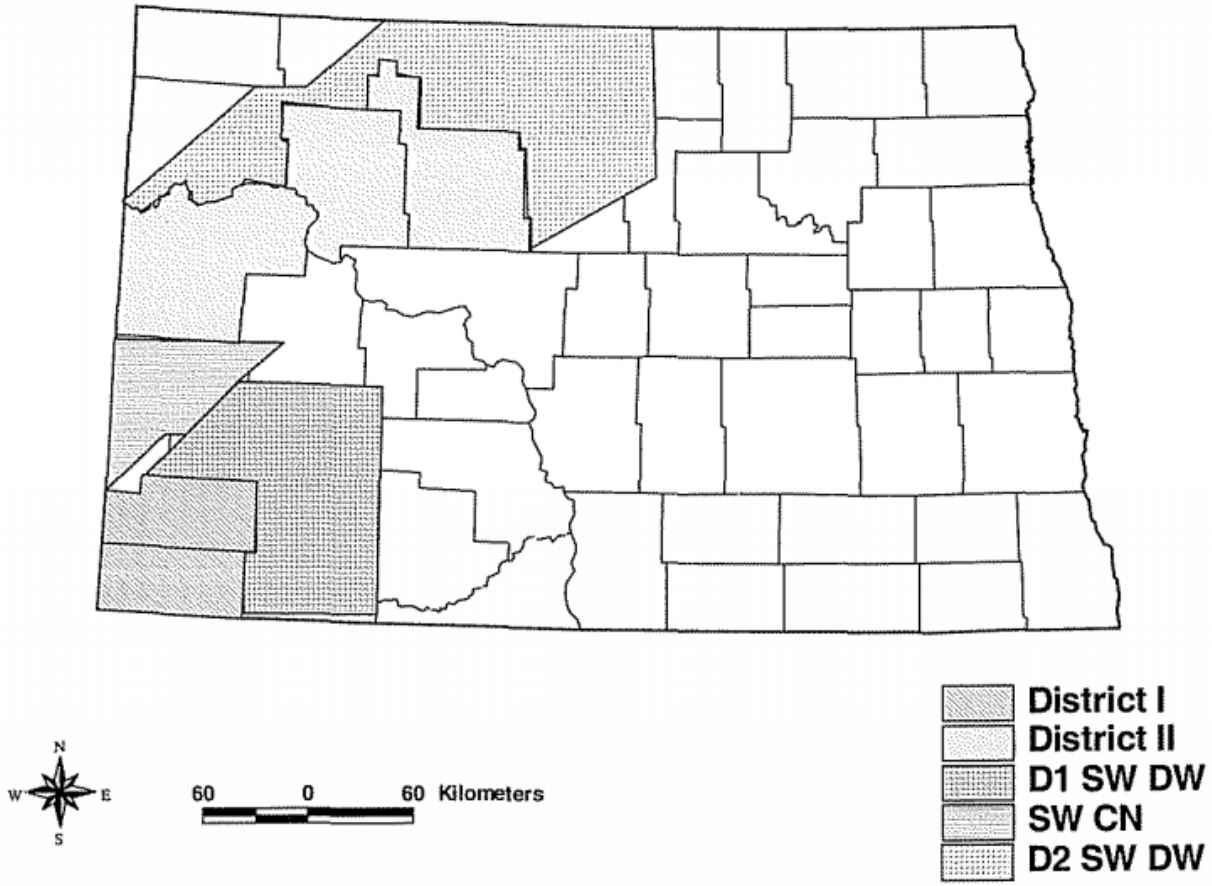


Figure 10. Southwest flow target, downwind, and control regions for Districts I and II.

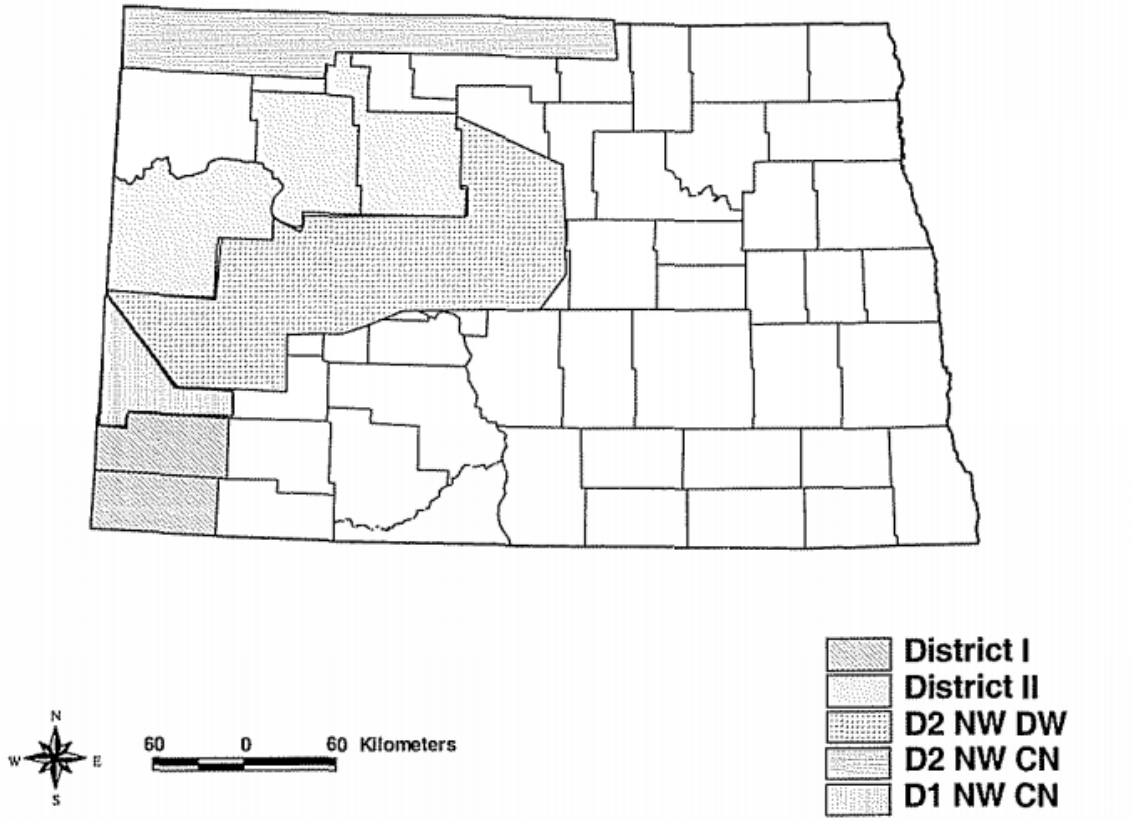


Figure 11. Northwest flow target, downwind, and control regions for both Districts I and II.

Methodology: Missing Data

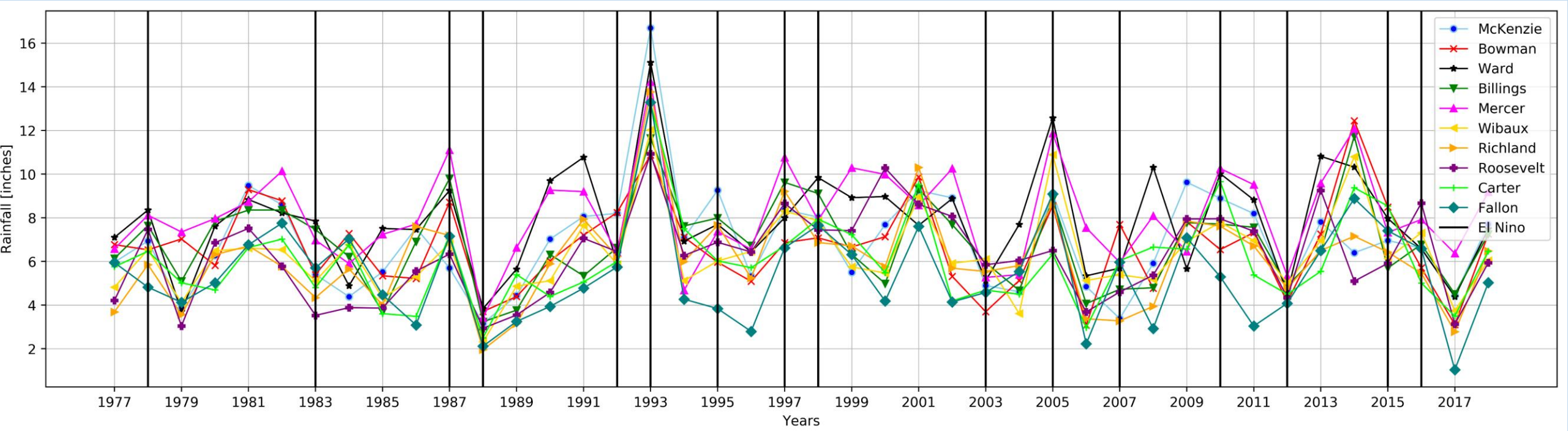
- For months with no rainfall reported by the station, a “NaN” was placed in the record.
- Most stations had had years labeled as “NaN”, with less than 40 % of all stations reporting the full 41 years.

Station	Year	June	July	August
451	1993	5.33	8.85	4.71
451	1994	**nan**	**nan**	0.33
451	1995	1.96	6.02	1.79
451	1996	**nan**	1.22	0.87
451	1997	2.42	4.76	1.84
451	1998	3.90	1.91	**nan**
451	1999	2.89	2.15	0.60
451	2000	4.02	2.82	0.70

Methodology: p-value

- P-values were calculated using Microsoft Excel's data analysis package through its t-test: Two-Sample Assuming Unequal Variance test as well as by hand calculating the p-values using the standard error and z-score.
- P-values were calculated for the single and double ratios during pre-NDCMP and NDCMP time periods.
- A predetermined p-value of 0.10 was used to determine if a result was statistically significant.

Weighted Rainfall With El Nino



Methodology: Control Region

- ND Controls
  - ‘Billings’: Billings and Golden Valley Counties
  - ‘Mercer’: McLean and Mercer Counties
- MT Controls
  - ‘Richland’: Richland and northern Dawson Counties
  - ‘Roosevelt’: Roosevelt and Sheridan Counties
  - ‘Wibaux’: Golden Valley County, ND., Wibaux, and southeast Dawson Counties
  - ‘Fallon’: Fallon County
  - ‘Carter’: Carter County

Previous Evaluations of the NDCMP

- Schaffner et al. (1983) conducted a three-section study on the economic benefit of additional growing season rainfall.
- Results for western ND showed a gain of approx. $53.0 million or $3.63 per planted acre was found with 0.85-1.15 inches of additional rain from June-August.

Previous Evaluations of the NDCMP

- Bangsund and Leistritz (2009) used a 5 and 10 % increase in rainfall to estimate value of growing season rainfall.
- With an increase of 5 % increase, an economic benefit of $8.4 million or $3.58 per planted acre would be seen annually.
- A 10 % increase in rainfall would result in $16 million annually or $6.84 per planted acre.

Previous Evaluations of the NDCMP

- Johnson (1985) evaluated rainfall for 1976 to 1982 in the target, downwind of target, and control regions.
- Results were found to not be statistically significant (p-value > 0.05) but showed an overall increase in rainfall downwind of the target site.
- Overall, there was no evidence for a rainfall increase in the target area.

Previous Evaluations of the NDCMP

- Smith et al. (1992) compared wheat yields for seeded and non-seeded counties before 1961 to wheats after 1975.
- Results found a 6% increase in wheat yields; however no statistical significance was found suggestion NDCMP was the cause.

Previous Evaluations of the NDCMP

- Smith et al. (1997) analyzed crop insurance claims from 1976 to 1988.
- Results showed 11 out of 13 years experienced loss ratios below the mean loss ratio.
- A multi-response permutation procedure two-sided p-values determined the 11 years were not due to random chance and likely a result of the NDCMP.

Methodology: Single Ratio

- Single ratio values are given in a decimal range where a 1:1 ratio is given as 1.0.
- Values such as 1.04 would suggest a positive 4 % difference in rainfall, which 0.96 would suggest a reduction 4 % difference in rainfall.