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Precipitation Evaluation of the North Dakota Cloud Modification Project (NDCMP) using rain Gauge Observations

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ABSTRACT

The North Dakota Cloud Modification Project (NDCMP) is a state-managed, cost-sharing weather modification program with a primary goal of reducing crop hail damage and a secondary goal of increasing precipitation. North Dakota has conducted NDCMP in western North Dakota since 1976. This analysis evaluates the 1977–2018 cloud seeding impact on rain gauge measured precipitation using an exploratory historical target/control statistical analysis. Three counties where seeding is conducted each year are target areas: McKenzie, Bowman, and Ward. Neighboring counties where little or no seeding occurred are control areas. Averages of available daily rain gauge measurements provide monthly and seasonal (June–August) area precipitation amounts for the target and control areas. Double ratio statistics are determined using the pre-NDCMP period of 1950–1975 and the NDCMP period of 1977–2018. The statistics use the McKenzie and Bowman target areas paired with four different control areas, along with the Ward target area paired with one control area. Six of eight McKenzie and Bowman target/control pairs have double ratios (1.01–1.12) possibly indicating higher target area precipitation during NDCMP. Additionally, two of eight ratios have a 95% statistical chance of being greater than 1.0. The Ward target/control comparison indicates no enhancement. The average of all nine target/control ratios is 1.03, consistent with a modest overall precipitation enhancement by NDCMP hail suppression operations.

1. Introduction

Evaluation of weather modification methods can include laboratory experiments, field observations, and numerical modeling. Laboratory experiments often involve evaluations of seeding material (e.g. Bruintjes et al., 2012), and the use of a cloud chamber (DeMott et al., 1995). While the Colorado State University Cloud Chamber is no longer available, a new cloud chamber at Michigan Technological University is available in the United States (Chang et al., 2016), along with several other Cloud Chambers around the world (e.g. Tajiri et al., 2013). Field observations typically evaluate direct and indirect effects of weather modification methods using observations such as precipitation or the seeding material amount in target area precipitation (e.g. Zipori et al., 2012). Numerical models can test concepts such as the dynamic seeding effect of silver iodide on cloud systems (Chen and Xiao, 2010). Weather modification programs typically try to implement the most scientifically robust evaluation methods using the best available observations and modeling support (e.g. Karacostas et al., 2018).

Evaluations of a weather modification program can include investigation of the physical processes involved or statistical analysis of observed results (e.g. Delene et al., 2011). Physical process studies can determine whether the environment and cloud systems are suitable for the weather modification method employed (e.g. Delene, 2016) or investigate the different processes involved in the “chain of events” between the operational procedures and rain reaching the ground (Bruintjes, 1999). The major processes, namely condensation growth, coalescence, the Bergeron-Findeisen-Wegener ice process, crystal aggregation, riming, drop freezing and secondary ice, involved in development of precipitation have been known for a long time (Braham, 1968). Experiments linking physical processes can be performed in a laboratory environment (e.g. DeMott et al., 1983) or in the atmosphere (e.g. French et al., 2018). Examples of North Dakota field projects studying physical processes of precipitation development include the North Dakota Thunderstorm Project (NDTP) in 1989 (Boe et al., 1992) and the North Dakota Tracer Experiment (NDTE) in 1993 (Bloomer and Detwiler, 1996).

In contrast to process studies, statistical analysis of weather modification programs offers a quantitative method to directly determine

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effectiveness by comparing results in treated areas to those in a defined, untreated, control area. Statistical studies have employed different evaluation techniques, which include exploratory statistical analysis (Krauss and Santos, 2004), use of target/control ratio analysis (Gabriel, 1999; Muralikrishna et al., 2009), floating control-target area analysis (Woodley and Rosenfeld, 2004), multiple linear regression analysis (Gabriel, 1999; He et al., 2014; Muralikrishna et al., 2009), and bootstrapping statistical analysis (Zhang et al., 2017). Scientists should evaluate statistical results carefully since other factors besides the cloud seeding program may be the cause of the apparent precipitation increase. This seems to be the case for the randomized Israel II experiment (1969–1975) where there apparently were preferred synoptic conditions during seeding periods (Levin et al., 2010; List et al., 1999).

Since the 1930s, North Dakota has been interested in increasing precipitation using weather modification methods. While methods for increasing precipitation were first proposed in the 1800s (Gatimann, 1891), it was not until 1946 that methods were developed based on valid science that took into consideration the massive nature of the atmosphere and the need to depend on triggering mechanisms (Schaefer, 1968). In North Dakota, weather modification efforts started in the 1950s using ground-based generators to deliver cloud seeding material (Miller and Fuhs, 1987). By the 1960s, aircraft delivery was the preferred method of releasing seeding material (Langerud and Moen, 1998). Initially these efforts were locally organized, and they generally aimed for hail damage reduction and precipitation increase over relatively small areas.

From 1969 to 1972, the North Dakota Pilot Project (NDPP) obtained data to evaluate cloud seeding effectiveness at enhancing precipitation in western North Dakota using randomized seeding trials (Dennis et al., 1975). The project was conducted in McKenzie County, with the addition of Mountrail and Ward Counties in 1972. Data were collected from radars, instrumented aircraft, and 67 daily precipitation gauges. The program used randomized seeding in order to collect observations of precipitation on days with similar clouds; hence, some days were seeded, and others not seeded. The analysis compared precipitation amounts on seeded and non-seeded days when a cloud model predicted a response to seeding. Analysis indicated that seeded days had an average of 1.5 times the precipitation of the unseeded suitable days. Additionally, seeding on model predicted unsuitable days had no effect (Dennis et al., 1975).

In 1976, a state-managed program, the North Dakota Cloud Modification Project (NDCMP), was started in western North Dakota with the primary goal of hail suppression to reduce crop loss (Schneider and Langerud, 2011). The NDCMP quickly added precipitation enhancement as a secondary goal. Counties that participated in NDCMP shared the cost of operations with the State. Operations are non-randomized where as many cloud systems as possible are targeted that meet the seeding criteria. The operational area changed from year-to-year due to variations in county participation. The NDCMP currently conducts hail suppression and rain enhancement in two western North Dakota areas from 1 June to 31 August (Weather Modification International, 2018). In 2018, Bowman, Slope, McKenzie, Williams, Mountrail, Ward, and Burke Counties were included in the operational area. Adams, Hettinger, and McLean counties previously participated but were not doing so in 2018. Bowman, Slope, McKenzie, Mountrail, and Ward counties have each participated in the NDCMP from 1977 to 2018 (42 years).

There have been several attempts to assess effects of NDCMP operations on precipitation in the target areas. Johnson (1985) evaluated the influence of NDCMP seeding operations on precipitation by comparing mean daily precipitation in target and downwind areas with unseeded control area for 1976 to 1982. The results were not statistically significant; however, suggested a precipitation increase downwind of the target site in July and a smaller increase in August. Furthermore, there was no suggestion of a precipitation increase within the target area.

Smith et al. (2004) studied cloud seeding effectiveness on precipitation using a target/control methodology on rain gauge data from the National Weather Service (NWS) Cooperative Observer Program (COOP). Eastern Montana (12 counties) was selected as the control area due to the rain gauges being upwind and not contaminated by precipitation from seeded clouds. Smith et al. (2004) considered 1950 to 1975 as the unseeded period since much less seeding occurred in North Dakota prior to 1976 and there were only a small number of Montana rain gauges before 1950. Rain gauge data showed an increase in summertime precipitation in target areas compared to control areas by a factor of 1.008; however, the results were not statistically significant (p-value of 0.322). The 90% confidence interval of the seeding effect was 0.91–1.10.

Wise (2005) analyzed the NDCMP effectiveness on precipitation using a daily target, control, and downwind approach based on prevailing storm motion using the North Dakota Atmospheric Resource Board Cooperative Observer Network (ARBCON) rain gauge data from 1977 to 2003. To determine the control/downwind areas, radar-derived storm tracks from 1999 to 2002 were used to determine target, control, and downwind regions for two general flow regimes over western North Dakota, northwest flow and southwest flow. Each seeding day from 1977 to 2003 was assigned to one of these flow regimes using North American Reanalysis data. COOP rain gauge data from 1931 to 1960 defined the change in target/control area precipitation in the absence of seeding for the two flow regimes. The District II (McKenzie, Mountrail, and Ward counties) 1977–2003 target/control and downwind/control seasonal precipitation ratios with southwest flow were greater than one and were statistically significant (p-values <0.10). Four out of seven combinations of district, flow regime and target or downwind status had at least 5% more seasonal precipitation in target or downwind areas compared to controls, while the other three combinations had $\pm 3\%$ differences.

This project's objective is to expand on previous research on NDCMP effectiveness using ARBCON and NWS COOP rain gauge measurements extending from 1950 through 2018. NDCMP secondary goal after hail suppression is precipitation enhancement in the target area, not in downwind areas; therefore, the analysis focuses on precipitation changes in the target area only and does not consider downwind regimes.

2. Material and methods

2.1. North Dakota Atmospheric Resource Board Cooperative Observer Network (ARBCON)

The ARBCON has used volunteer observers since starting in 1977. Volunteers changed often; therefore, many stations only have data for one year and only a few sites report over the whole NDCMP period of 1977 to 2018. The total number of ARBCON rain gauges in the project area generally decreased over the period 1977–2018. For example, the number of rain gauges in McKenzie County began in 1977 with over 50 gauges; however, the number decreased to approximately half of this number by 2002, then increased to peak again at 38 in 2010, followed by a steep decline thereafter (Fig. 1). The rain gauge numbers in other target/control areas have similar variations to those in McKenzie County, which results in a seasonal average of 164 total ARBCON rain gauges in 1977 that decreased to 94 in 2018.

For most of the NDCMP era, ARBCON observers used a "Tru-Chek" wedge-shaped rain gauge and reported daily measurements monthly on postage paid, reporting cards. All observers used the Tru-Chek wedge gauge from 1977 until the end of 2010. In the fall of 2010, some observers began making snowfall and snow depth observations. Those observers conducting snow measurements began using a 4-in. diameter cylindrical gauge. The rain-only observers also started receiving the 4-in. cylindrical gauges as their wedge gauges needed replacement.

The wedge-shaped rain gauges measure precipitation to the nearest hundredth of an inch below 1.0 in. and to the nearest five hundredths of an inch from 1.0 to 6.0 in. The cylindrical gauges consist of a narrow

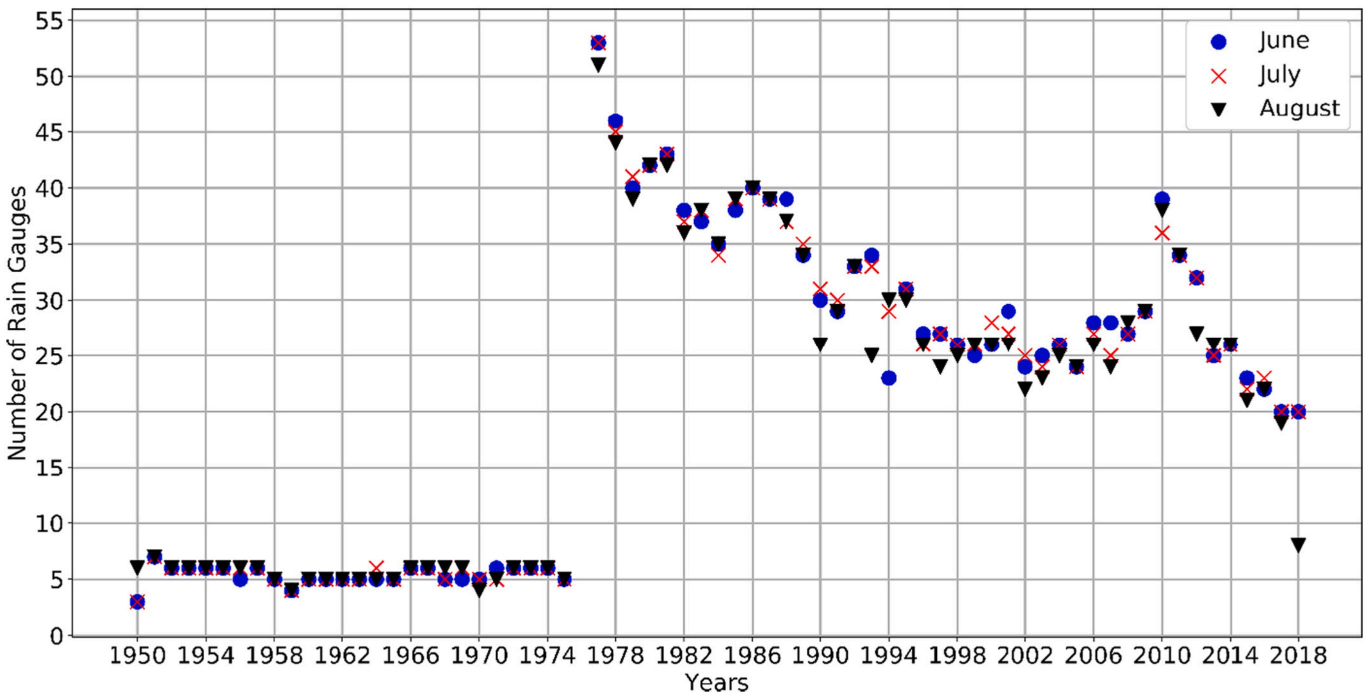

Fig. 1. Time series plot showing number of available National Weather Service (NWS) Cooperative Observer Program (COOP) and North Dakota Atmospheric Resource Board Cooperative Observer Network (ARBCON) rain gauges for McKenzie County for June (blue), July (red), and August (black). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

cylinder within an outer 4-in. cylinder. The ARBCON observers measure daily precipitation less than 1.0 in. directly in the inner cylinder. When precipitation is greater than 1.0 in., water overflows from the inner cylinder into the larger outer cylinder. When overflow occurs, ARBCON observers measure water in the inner cylinder to the nearest 0.01 in. and empty the cylinder. Observers then pour water from the outer cylinder into the inner cylinder for measurement and repeat as many times as necessary. Therefore, ARBCON observers measure precipitation up to 10.0 in. with a precision of 0.01 in.

The ARBCON observers normally conduct measurements from April 1 to September 30; however, some observers do not start until June 1 when cloud seeding operations begin. Observers conduct precipitation measurements once a day, typically at 0800 AM local time. Parts of the NDCMP area are in the Mountain Time Zone and parts in the Central Time Zone. In either time zone, the measured precipitation typically represents the previous day's precipitation since most central United States summertime convection occurs during the afternoon and evening local time (Liu and Li, 2016).

2.2. National Weather Service (NWS) Cooperative Observer Program (COOP)

The NWS COOP has more than 10,000 volunteer observers across the United States. Our analysis uses measurements from 60 NWS COOP observers that reported 24-h precipitation in the target/control areas for at least one year between 1977 and 2018. NWS COOP observers use 8-in., open mouth can, rain gauges, which measure precipitation up to 20 in. to a tenth of an inch. For both the NWS COOP and ARBCON, database administrators manually enter rain gauge measurements and check questionable measurements before inclusion. Additionally an automated algorithm reviews the NWS COOP data set; however, our review uncovered questionable daily precipitation measurements, which have been removed from our analyzed data set (Tuftedal and Delene, 2020a).

A digitized precipitation data set can have several issues that include observers only reporting when there is precipitation, nonstandard measurement time, and missing data. Missing data (i.e. missing reports on any given day throughout a given month) results in different numbers of gauges reporting on different days of the same month. If a station did not contain a daily report for each day in a given month, the station was not included in the data set. To have as many observations as possible, the analysis uses a combined ARBCON and NWS COOP data sets to evaluate the NDCMP precipitation. Evaluation of ARBCON and NWS COOP gauge pairs within 10 km of each other show that multi-annual and annual measurements are within approximately half an inch per year and have a correlation of 0.998 (Langerud and Gilstad, 2003); therefore, there should not be any biases introduced by using the combined data set.

2.3. Methodology

The analysis uses target and control areas defined mainly by grouping counties (Fig. 2). For example, the Bowman target area is formed by combining Bowman and Slope Counties. Other target/control areas contain portions of neighboring counties or may be missing small portions of their namesake county, which is evident by comparing Fig. 2 and Fig. 3. The Bowman, McKenzie, and Ward target areas have participated in the NDCMP for the entire 1977 to 2018 period. The control areas are close to their paired target areas so meteorological factors affecting precipitation are similar. Storms in western North Dakota typically move from west to east; therefore, control areas are generally west of their respective target area so seeded storms would be expected to move away from the control area and not influence control area precipitation amounts (DeFelice et al., 2014). North Dakota control areas (Fig. 3) are 'Billings' and 'Mercer'. Montana control areas are 'Richland', 'Roosevelt', 'Wibaux', and 'Fallon'. Control area counties have not participated in the NDCMP, or participated for a relatively short period (less than 10 years), compared to the analyzed period of 42 years. The control areas are less than 100 km across, except for the Mercer control area. Control areas within eastern Montana areas do not necessarily include all gauges in a county since some rain gauges are not included due to being a very short distance from the North Dakota border.

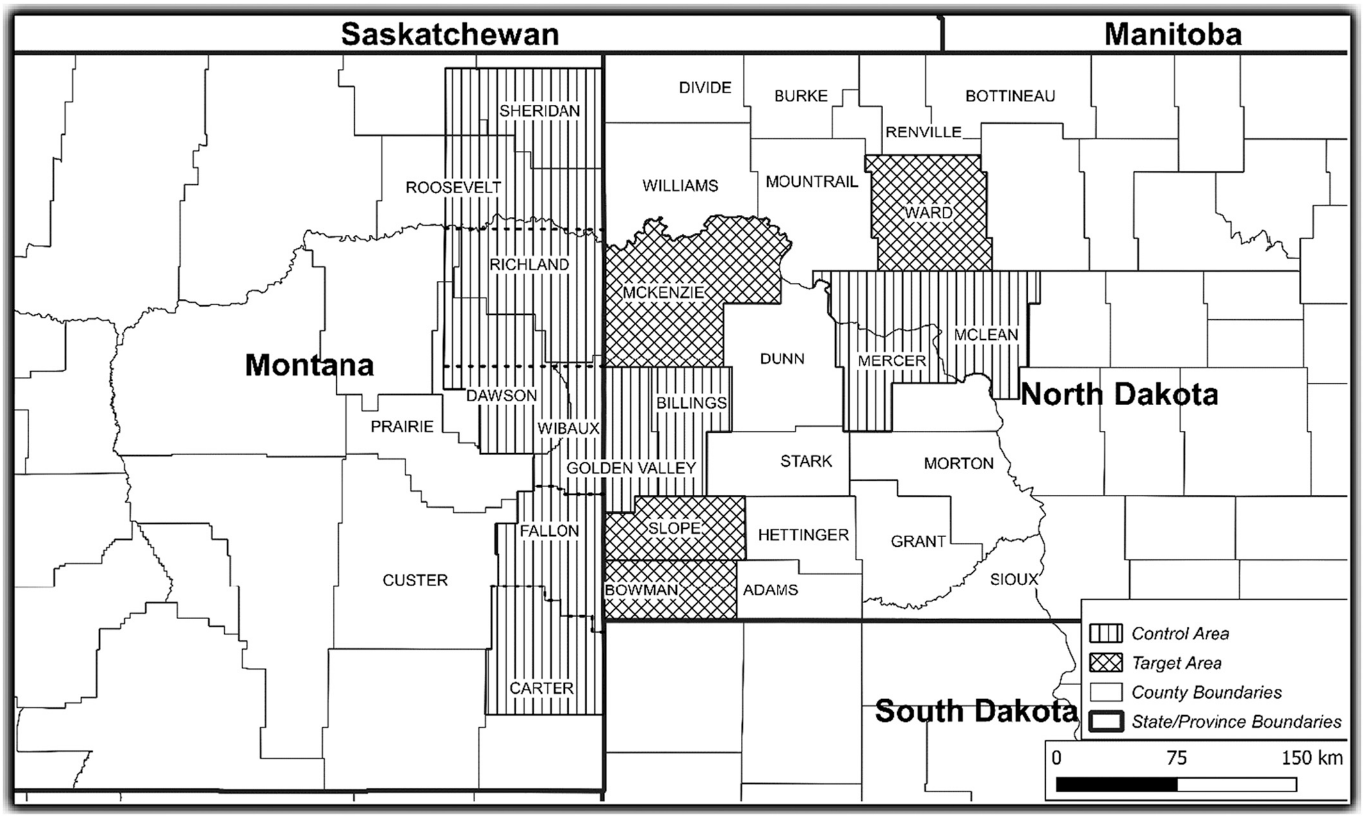

Fig. 2. A political map showing North Dakota and surrounding states that have counties near the North Dakota Cloud Modification Project (NDCMP) operational area. Crossed lines highlight the target area and vertical lines highlight the control area.

The analysis pairs the McKenzie target area with control areas of Richland, Roosevelt, Wibaux, and Billings, and the Bowman target area with control areas of Carter, Fallon, Wibaux and Billings. All target areas have multiple control areas, except the Ward target area for which the only suitable control area is Mercer. Other possible control areas for Ward are either target areas in which the NDCMP carries out seeding operations, or downwind of seeding operations. Even the Mercer control area may have some downwind contamination from seeding in the McKenzie target area. Additionally, McLean County (part of the Mercer control area) briefly participated in NDCMP which could dilute any indication of a seeding effect for Ward County.

Monthly precipitation for the NDCMP period (1977–2018) and the pre-project period (1950–1975) uses all stations within the combined, quality assured data set. Limited cloud seeding occurred in the North Dakota control and target areas in the pre-project period, which included short-term limited operations organized by groups of farmers and several scientific randomized seeding trials. These seeding trials, such as the NDPP mention previously, randomized operations based on day. The research programs generally ran for only one year or at most a few years. In addition, there were NDCMP operations in portions of some of the control areas for short periods. Such cloud seeding in control areas may reduce any apparent effect of seeding found in our statistical analysis.

Station observations in a target or control area are only included in estimating average monthly precipitation if a complete record exists for at least one of the months June, July, or August. The equation for monthly precipitation total at a specific station (S) is,

$$M_s = \sum_{d=1}^{N} Rain_d \tag{1}$$

where *Rain* is daily precipitation on a specific day (d), and N is number of days in the month. The equation for area averaged monthly precipitation is,

$$\overline{T}_{area} = \frac{\sum_{s=1}^{n} M_s}{n} \tag{2}$$

where n is the number of valid stations within the area. The summation in Eq. (2) is over all stations (S) within the county (area) and for the monthly station precipitation totals given by Eq. (1). The target/control single ratio equation (Breed et al., 2013; Gabriel, 1999) is

$$SR = \frac{\sum_{n=1}^{years} \overline{T}_{target}^{June,July,August,or\ Seasonal}}{\sum_{n=1}^{years} \overline{T}_{control}^{June,July,August,or\ Seasonal}} \tag{3}$$

where $\overline{T}$ is calculated using Eq. (2) with June, July, August, or seasonal precipitation for target and control areas. The single ratio uses the 42-year project period and the 26-year pre-project period.

To account for regional and large scale natural climate variations between the pre-project period and the NDCMP period that affected both target and control areas, a double ratio (DR) is used (Breed et al., 2013; Gabriel, 1999). The double ratio equation is

$$DR = \frac{SR_{1977-2018}}{SR_{1950-1975}} \tag{4}$$

where $SR_{1977-2018}$ is the single ratio from the NDCMP years (1977–2018), and $SR_{1950-1975}$ is the single ratio from the pre-project years (1950–1975). The double ratio accounts for natural variations that influence both the control and project areas by using the pre-project years to estimate the natural single ratio for each target-control pair. If the single ratio is different for the project years, it is possible that NDCMP cloud seeding is responsible for this difference. Using this normalization assumes the climate did not change in terms of spatial precipitation correlations of summer-time precipitation in western

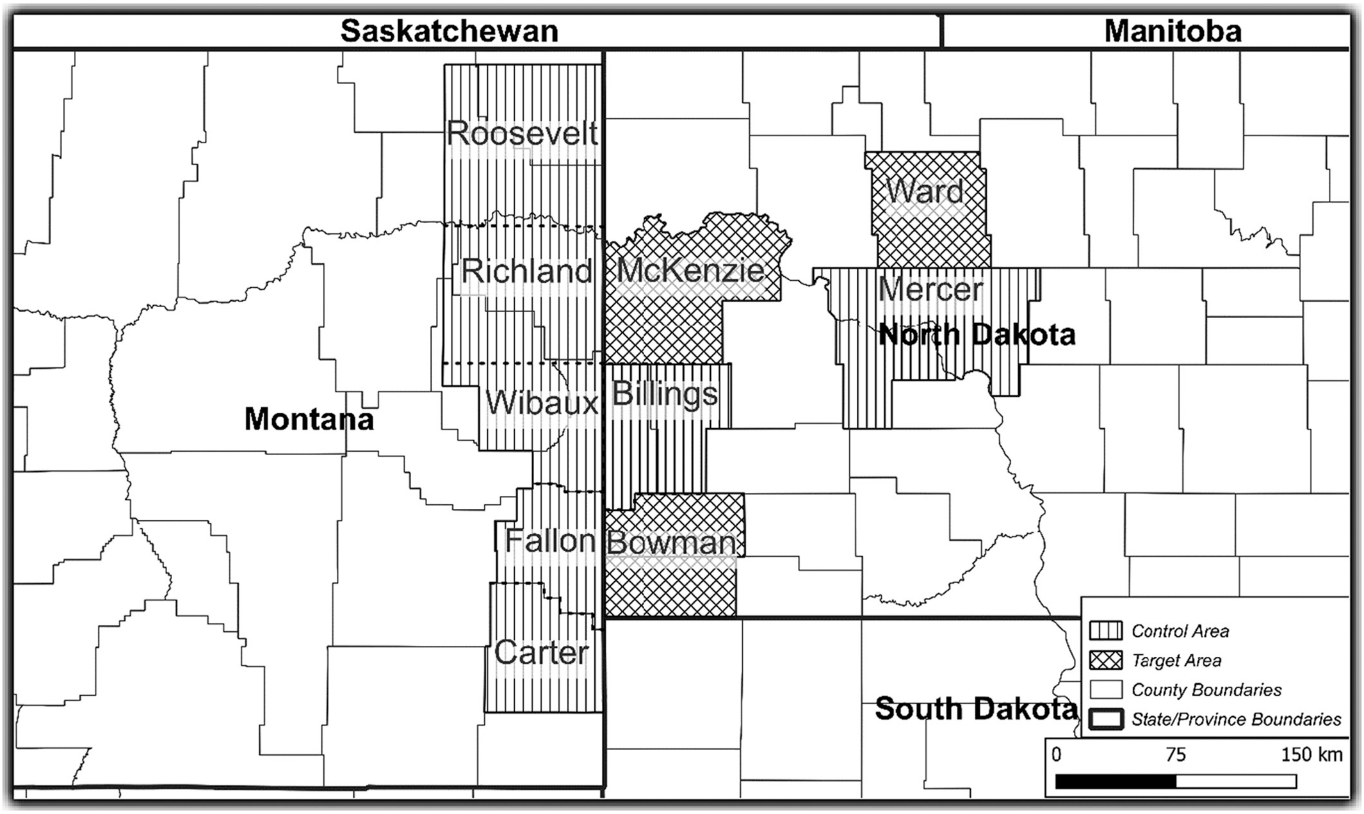

Fig. 3. Map showing the cloud seeding target and control areas. The Bowman area includes Bowman and Slope Counties. The Billings area includes Billings and Golden Valley counties. The Wibaux area includes Wibaux County, as well as part of Dawson County. The Mercer area includes Mercer and Mclean counties. The Richland and Roosevelt areas in Montana includes parts of several counties. McKenzie, Ward, Carter, and Fallon areas correspond to their respective counties.

North Dakota between the two periods.

To determine statistical uncertainty and confidence intervals of double ratios, bootstrapping is used to randomly resample the data set multiple times (Hesterberg et al., 2005). Bootstrapping does not assume a Gaussian, or any specific distribution type, for the data set population. Bootstrapping assumes that each observation is a random sample selected from the population and the resulting samples are representative of the population. To determine statistical significance, the analysis uses the one-tailed statistical test applied to particular target/control pairs. The one-tailed statistical test checks if the critical area of a distribution is greater than, or less than, a specified value (Lane, 2003). For example, a double ratio above 1.0 from bootstrapping indicates the possibility of an increase in precipitation due to cloud seeding. If 95% of a bootstrapped sample of double ratios are above 1.0, this indicates a 95% likelihood of a precipitation increase. The methodology uses 95% likelihood to indicate statistical significance.

The Mann-Whitney *U* test is a non-parametric test that can be applied to non-normally distributed data in place of an unpaired *t*-test (Shier, 2004) and can determine whether two independent samples are from populations having the same distributions. The data used for the Mann-Whitney U test are single ratios from 1950 to 1975 and 1977 to 2018 for McKenzie paired with Billings, Wibaux, Richland and Roosevelt; Bowman paired with Billings, Wibaux, Carter and Fallon; and Ward paired with Mercer. The test determines if single ratios are from the same population. In this test, having a small *p*-value indicates that the target and control data are from different populations and are significantly different from each other; while, a large p-value indicates the data comes from the same population and the ratios are statistically the same.

3. Results and discussion

Table 1 shows average monthly and seasonal countywide

Table 1
Monthly and seasonal (June, July, and August) area-wide precipitation using measurements from National Weather Service (NWS) Cooperative Observer Program (COOP) for 1950–1975, and North Dakota Atmospheric Resource Board Cooperative Observer Network (ARBCON) and NWS COOP for 1977–2018.

County	June (cm)		July (cm)		August (cm)		Seasonal (cm)	
	1950–1975	1977–2018	1950–1975	1977–2018	1950–1975	1977–2018	1950–1975	1977–2018
McKenzie	8.71	7.52	5.22	6.07	4.31	4.04	18.25	17.63
Bowman	9.26	7.60	5.28	5.27	3.94	4.00	18.48	16.88
Ward	8.82	8.66	5.70	6.50	5.09	4.73	19.61	19.90
Billings	10.29	7.52	5.47	5.90	4.66	4.50	20.42	17.92
Mercer	8.87	8.87	5.95	6.96	4.86	5.08	19.68	20.62
Wibaux	9.87	7.17	5.30	5.57	4.47	4.29	19.64	17.03
Richland	7.70	6.38	4.90	5.40	4.12	3.43	16.72	15.22
Roosevelt	7.17	6.66	4.79	5.69	4.23	3.37	16.19	15.72
Carter	9.78	8.32	5.52	5.45	3.88	4.54	19.18	18.31
Fallon	7.67	6.34	4.37	4.10	3.14	3.25	15.18	13.69

precipitation calculated for the pre-project and NDCMP years. June has the most precipitation in all counties, July precipitation is in the middle, and August has the least precipitation. Averaging measurements over county-sized areas and over a month or a season smooths the precipitation record by removing daily fluctuations due to individual storms affecting small portions of target and control areas. Precipitation generally increases from west to east, which corresponds with increasing distance from the Rocky Mountains that is consistent with the climatological precipitation pattern shown in Fig. 4.

The target and control area precipitation have correlations for pre-project and NDCMP periods ranging from approximately 0.4 to 0.8 (Table 2). McKenzie area precipitation is most highly correlated with Richland in both the pre-project (0.81) and NDCMP (0.90) periods. Wibaux and Roosevelt correlations with McKenzie are similar in magnitude, while the correlation for Billings is less in both periods. Correlations in general are higher in the NDCMP period compared to the pre-project period. The Bowman target area is highly correlated with the Carter and Fallon control areas, with slightly better correlations in the pre-project period. Wibaux and Billings areas correlate slightly less well with Bowman. In general, target/control correlations are highest with control areas to the southwest of the target area. The fact that the order in which the target areas correlate with neighboring control areas is very similar in both pre-NDCMP and NDCMP periods argues against a major difference between periods in how precipitation systems affect these areas.

The pre-project period has three out of nine target areas naturally receiving more seasonal precipitation than control areas as indicated by single ratios (Eq. (3)) greater than 1.0 (Table 3). The single ratios for the NDCMP period show an increase in the number of target areas receiving more precipitation than control areas. Out of the nine possible target/control combinations, four single ratios show more precipitation in the target area than the control area. While this change from pre-project period to the operational period could be due to a regional convective storm regime shift, the similarity of the correlation matrices in Table 2 argue against a major change. There is a notable increase for McKenzie/Billings and McKenzie/Wibaux single ratios from pre-NDCMP to NDCMP periods. Target/control single ratios less than or equal to 1.0, do not indicate a decrease in target area precipitation due to seeding since the target areas typically received less rain fall than the control areas for the pre-project period.

Table 4 indicates that six out of nine target/control pairs have seasonal double ratios greater than one. The seasonal double ratios for McKenzie/Billings and McKenzie/Wibaux showed the largest increases among all target/control pairs during the NDCMP period, which are 10 and 12%, respectively. These can be interpreted as possible increases in precipitation in the target area over that expected based on precipitation in the control area. The double ratio for McKenzie/Richland indicates a possible precipitation increase of 6%. The 4th McKenzie double ratio is 1.0. Bowman double ratios exceeded 1.0 except for Bowman/Carter (0.95), with the highest double ratio being 1.05 (Bowman/Wibaux). The seasonal Ward/Mercer double ratio is slightly less than one, which could be interpreted as a possible decrease in precipitation.

Bootstrapping (Table 5) provides insight into statistical robustness of the double ratio results by providing 95% confidence intervals. In some cases, the entire double ratio 95% confidence interval is above 1.0. For example, the distribution of double ratios for McKenzie/Wibaux shows an increase in precipitation in more than 95% of bootstrapped samples (Fig. 5). Based on the one-tailed significance test being above 1.0, McKenzie/Billings, McKenzie/Wibaux, and McKenzie/Richland target/control pairings show 90% or greater likelihood of a possible increase in target area precipitation during the NDCMP period over that expected based on control area precipitation. McKenzie/Roosevelt, Bowman/Carter and Ward/Mercer double ratios indicate possibly either no increase or slight decrease and the one-tailed significance indicates low confidence in the likelihood of a target precipitation change during the NDCMP period. These results are similar to those of Wise (2005) who showed an increase in some target/control pairings but not all.

Additionally, Table 5 shows results from the Mann-Whitney U statically test calculated for the single ratios for 1950–1975 and 1977–2018. The *p*-values calculated for McKenzie/Wibaux and McKenzie/Richland are statistically significant for a p-value <0.10. This infers that for these target/control pairs, the single ratios for pre-NDCMP and NDCMP periods are not from the same population and there is a significant difference between the two data sets. McKenzie/Billings pair p-value of 0.128 is larger than the p-value criteria calculated for the two-tailed test, which indicating that the single ratios from the two periods may be part

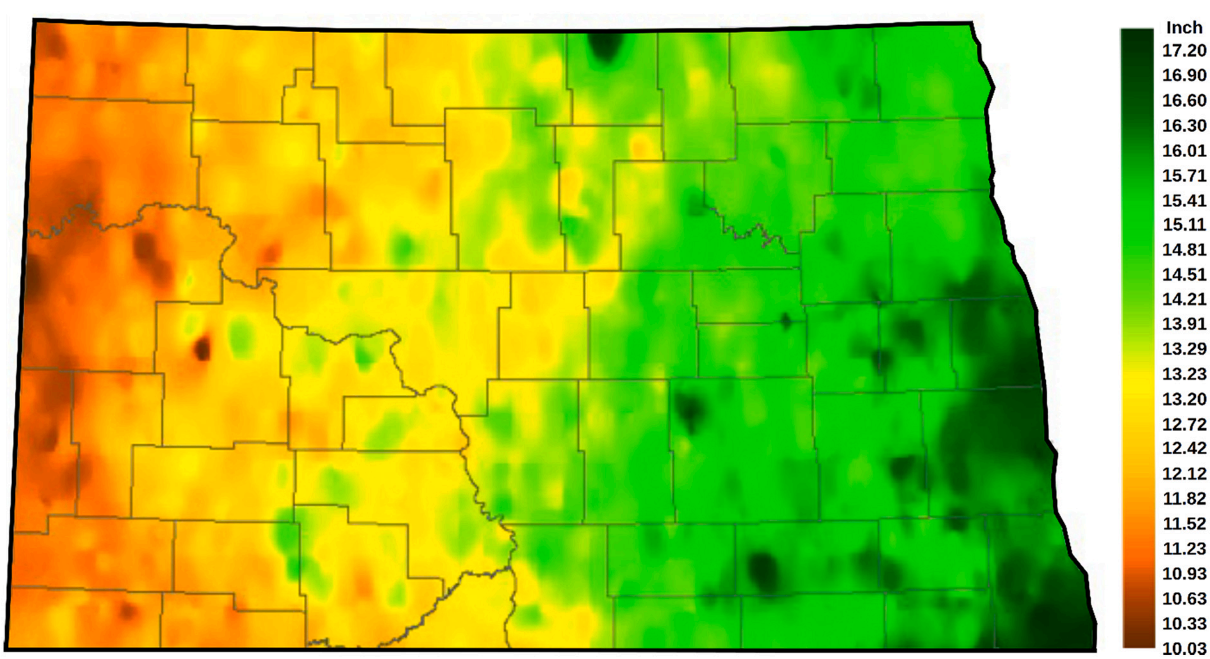

Fig. 4. Plot showing 30-year (1977–2006) average precipitation over North Dakota for April through September. Image adapted from plot obtained from the North Dakota State Water Commission Web site (https://www.swc.nd.gov/arb/NDARBCON/30Year.html).

Table 2
Top table shows the correlations between target and control areas for the pre-project period of 1950–1975. The bottom table shows the correlations between target and control areas for the project period of 1977–2018.

County	McKenzie	Bowman	Ward	Billings	Mercer	Wibaux	Richland	Roosevelt	Fallon	Carter
McKenzie	1.00	0.46	0.67	0.59	0.63	0.73	0.81	0.68	0.55	0.49
Bowman	0.46	1.00	0.47	0.58	0.75	0.65	0.35	0.33	0.71	0.76
Ward	0.67	0.47	1.00	0.52	0.64	0.61	0.53	0.55	0.52	0.49
Billings	0.59	0.58	0.52	1.00	0.54	0.85	0.55	0.48	0.56	0.49
Mercer	0.63	0.75	0.64	0.54	1.00	0.56	0.47	0.46	0.64	0.54
Wibaux	0.73	0.65	0.61	0.85	0.56	1.00	0.74	0.47	0.70	0.61
Richland	0.81	0.35	0.53	0.55	0.47	0.74	1.00	0.65	0.57	0.47
Roosevelt	0.68	0.33	0.55	0.48	0.46	0.47	0.65	1.00	0.38	0.50
Fallon	0.55	0.71	0.52	0.56	0.64	0.70	0.57	0.38	1.00	0.62
Carter	0.49	0.76	0.49	0.49	0.54	0.61	0.47	0.50	0.62	1.00

County	McKenzie	Bowman	Ward	Billings	Mercer	Wibaux	Richland	Roosevelt	Fallon	Carter
McKenzie	1.00	0.66	0.79	0.81	0.70	0.81	0.90	0.83	0.68	0.67
Bowman	0.66	1.00	0.62	0.75	0.62	0.74	0.70	0.57	0.85	0.78
Ward	0.79	0.62	1.00	0.70	0.87	0.73	0.74	0.75	0.66	0.62
Billings	0.81	0.75	0.70	1.00	0.70	0.95	0.84	0.65	0.75	0.70
Mercer	0.70	0.62	0.87	0.70	1.00	0.72	0.66	0.69	0.63	0.60
Wibaux	0.81	0.74	0.73	0.95	0.72	1.00	0.87	0.69	0.80	0.73
Richland	0.90	0.70	0.74	0.84	0.66	0.87	1.00	0.82	0.73	0.71
Roosevelt	0.83	0.57	0.75	0.65	0.69	0.69	0.82	1.00	0.56	0.54
Fallon	0.68	0.85	0.66	0.75	0.63	0.80	0.73	0.56	1.00	0.78
Carter	0.67	0.78	0.62	0.70	0.60	0.73	0.71	0.54	0.78	1.00

Table 3
Single ratios (Eq. 3) of target/control area-wide average precipitation using pre-project period of 1950–1975 and project period of 1977–2018. Averages use all valid National Weather Service (NWS) Cooperative Observer Program (COOP) and North Dakota Atmospheric Resource Board Cooperative Observer Network (ARBCON) observations. Seasonal single ratios include precipitation averages from June, July, and August.

Target/Control	June		July		August		Seasonal	
	1950–1975	1977–2018	1950–1975	1977–2018	1950–1975	1977–2018	1950–1975	1977–2018
McKenzie/Billings	0.84	1.00	0.95	1.03	0.92	0.89	0.89	0.98
McKenzie/Richland	1.13	1.17	1.06	1.12	1.04	1.17	1.09	1.15
McKenzie/Wibaux	0.88	1.05	0.98	1.09	0.96	0.94	0.92	1.03
McKenzie/Roosevelt	1.21	1.12	1.09	1.06	1.02	1.20	1.12	1.12
Bowman/Billings	0.89	1.01	0.96	0.89	0.84	0.88	0.90	0.94
Bowman/Wibaux	0.93	1.06	0.99	0.94	0.88	0.93	0.94	0.99
Bowman/Carter	0.94	0.91	0.95	0.96	1.01	0.88	0.96	0.92
Bowman/Fallon	1.20	1.19	1.20	1.28	1.25	1.23	1.21	1.23
Ward/Mercer	0.99	1.01	0.96	0.93	1.04	0.93	0.99	0.96

Table 4
Target/control double ratios (Eq. 4) using single ratios from the project period of 1977–2018 over single ratios from pre-project period of 1950–1975. Seasonal double ratios include precipitation averages from June, July, and August.

Target/Control Pair	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	0.95
Bowman/Fallon	0.99	1.07	0.98	1.01
Ward/Mercer	1.02	0.97	0.89	0.97

of the same population. The p-values for McKenzie/Roosevelt pair, all Bowman pairs, and Ward/Mercer pair are not statistically significant and may likely be from the same population. The Mann-Whitney test results show similar trends to the bootstrapping results with overall weaker statistical significance.

Our discussion focuses on seasonally averaged results, as they are less noisy than monthly averages. Different target-control pairs yield different double ratios, and hence possible precipitation changes due to NCMP cloud seeding, for the McKenzie and Bowman target areas. This

Table 5
Table showing bootstrapped target/control double ratio (DR) statistics using area-wide average seasonal precipitation, Mann-Whitney U test statistic (U test) and associated p-values. The bootstrapping method with 10,000 iterations generates the 95% confidence interval. A one-tailed significance test on the bootstrapped double ratios provides the percentile above 1.0.

Target/Control Pair	DR	95% Confidence	Significance > 1.0	U test	p-value
McKenzie/ Billings	1.10	0.99–1.22	**96.5%**	667.0	0.128
McKenzie/ Wibaux	1.12	1.01–1.23	**98.5%**	720.0	0.029
McKenzie/ Richland	1.06	0.98–1.15	**94.0%**	687.0	0.076
McKenzie/ Roosevelt	1.00	0.90–1.10	**46.5%**	552.0	0.945
Bowman/ Billings	1.04	0.93–1.16	**75.0%**	589.0	0.592
Bowman/ Wibaux	1.05	0.94–1.17	**85.0%**	620.0	0.354
Bowman/Fallon	1.01	0.91–1.12	**60.0%**	598.0	0.516
Bowman/Carter	0.95	0.86–1.05	**19.0%**	561.0	0.855
Ward/Mercer	0.96	0.87–1.07	**27.5%**	512.0	0.672

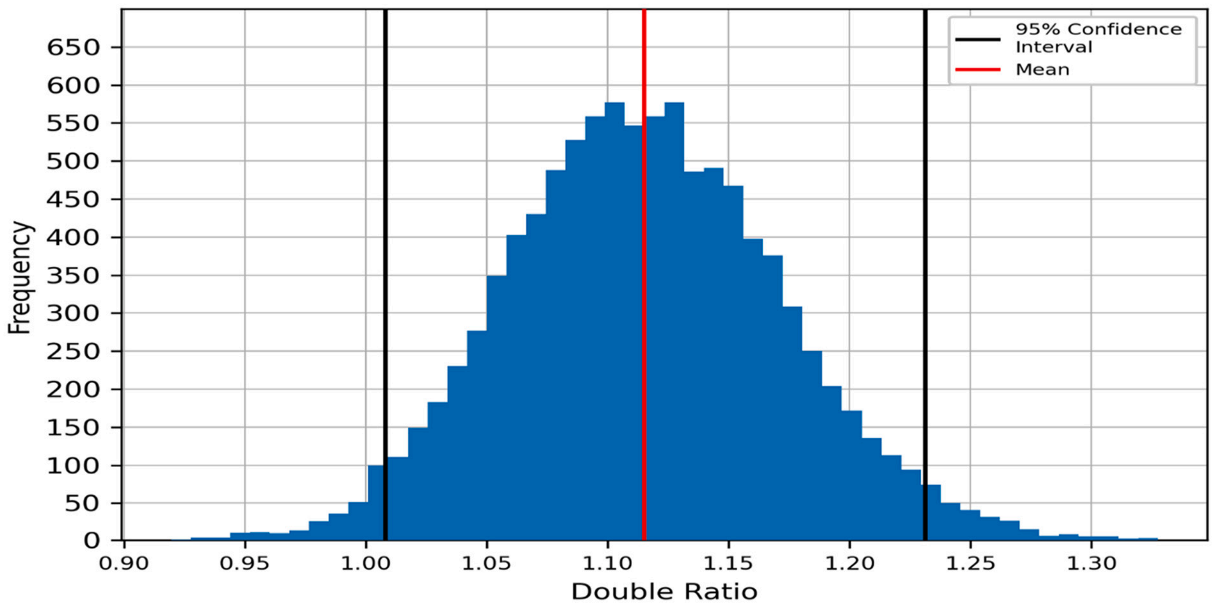

Fig. 5. Plot showing the distribution of double ratios from area-wide, seasonal precipitation averages for McKenzie/Wibaux (Fig. 3) pairs. The bootstrapping method with 10,000 iterations generates the distribution. The red line denotes the mean double ratio and the black lines enclose the 95% confidence interval. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

difference in double ratios can be due to different pair correlations and different statistical skill in using control area precipitation to predict natural target area precipitation in the absence of NDCMP operations. Variation in results between control pairings also could be due to contamination by short and limited operational or research programs conducted in the McKenzie and Bowman areas in the pre-project period that contributes some seeding enhancements and result in the NDCMP single ratios being more similar. Additionally, there were some limited operations in the control area of McLean County during the NDCMP period.

Not having any way to determine how representative the different double ratios are for different target/control pairs in Table 5, we summarize using simple averages. Averages seem appropriate since the same organization conducted the operations in each target areas using similar methods and the storms developed in the same regional environments. If seeding led to precipitation increases in target areas, the increases should be in the same proportion in each target area, on average. It makes sense that an average of double ratios is a better estimate of expected precipitation increase than any single value. If we interpret the seasonal double ratio results as indications of seasonal precipitation increases due to NDCMP seeding activities, the average factor increase in precipitation in target areas is 1.07 for McKenzie, 1.01 for Bowman, and 0.97 for Ward. An average for all seasonal target/control pairs is 1.03.

The highest double ratios for both McKenzie and Bowman target areas are with Wibaux and Billings control areas, which in both cases have some of the lower correlation coefficients among the available target-control combinations. This could be due to a possible shift in natural precipitation patterns in the region between pre-project and project periods. It is also possible the natural pattern did not change but there is an effect due to the difference in number of reporting stations and location differences between the COOP-only observations of the pre-project period and the COOP plus ARBCON locations during the NDCMP period.

Using the mean McKenzie County double ratio (Table 5) of 1.07 indicates the possibility of an average seasonal precipitation increase of 7% in this region. The averaged seasonal McKenzie precipitation for 1977–2018 is 17.63 cm, which includes the possible 7% increase due to cloud seeding. Without cloud seeding, the average McKenzie precipitation would be 16.40 cm; therefore, the 7% increase is equivalent to 1.23 cm (0.48 in.) of additional summer-time precipitation. The increase is smaller but of the same order of magnitude as the 2.54 cm (1.0 in.) of additional summer-time precipitation due to seeding extrapolated from analysis of the randomized seeding experiments during the North Dakota Pilot Project (NDPP) (Dennis et al., 1975) conducted in McKenzie County from 1969 to 1972. It is important to note that seeding operations during the NDPP focused on precipitation enhancement and the NDCMP operations focused on hail suppression; additionally, there were some differences in operational procedures between the two projects.

Quantifying area-wide summer precipitation in western North Dakota is difficult using rain gauge observations due to the high spatial variability of convective rain (Silverman et al., 1981). Their recommendation that a minimum of four gauges is needed to adequately monitor precipitation from a convective storm is probably often not met in our study. Higher density rain gauge networks provide better precipitation measurements. As NDCMP conducts more years of operations, use of rain gauge measurements from the pre-project period in the double ratios becomes more problematic since spatial correlations in precipitation may change with time. Additionally, using the 1950–1975 pre-project period is problematic due to limited cloud seeding being conducted in some target and some control areas shown in Fig. 3 during this period. Therefore, interpretation of the results depends on the assumption about how much effect these early limited seeding efforts had on the monthly and seasonal precipitation.

The use of the pre-project period to account for natural spatial correlations in precipitation is necessary since NDCMP is a non-randomized seeding operation with every possible storm treated when meeting the seeding criteria and having an aircraft available. In addition, seeding may contaminate downwind North Dakota control areas of Billings and Mercer. These issues of contributions by seeding during the pre-NDCMP period and contamination of control areas with seeding material during the NDCMP reduces any apparent seeding effect discernible in our analysis by making single ratios in the target/control areas and pre-project/project periods more similar. Therefore, using pre-project target/control precipitation correlations as a normalization factor has limitations. An analysis like that presented here would benefit from more rain gauges in the target/control areas and additional years of

NDCMP seeding operations; however, the pre-project data set is fixed. The analysis cannot make use of additional pre-project years by going further back in time since there is insufficient rain gauge coverage over western North Dakota and eastern Montana before 1950.

4. Conclusion

Evaluation of the NDCMP's effect on target area precipitation is conducted using long-term rain gauge measurements and a target/control methodology. The analysis uses single and double ratios of target/control, area-wide precipitation for the months of June, July, and August, and the summer season. The summer season double ratios have six of the nine target/control pairs where targets receive at least 2%, or more, precipitation than expected based on the corresponding control area. Based on the one-tailed significance test, six of nine double ratios indicate precipitation increases with two being statistically significant at the 95% confidence level and three being statistically significant at the 90% confidence level. Averaged double ratios of target areas with multiple control areas indicate possible changes in precipitation due to NDCMP operations with ratios of 1.07 for McKenzie County, 1.01 for Bowman County, and 0.97 for Ward County. For all nine target/control pairs, the seasonal average ratio is 1.03. These are lower limit ratios due to contamination of the pre-project period data by some seeding activity and possible effects of seeding on control areas during the NDCMP period. Although changes in target/control correlations in natural precipitation between pre-NDCMP and NDCMP periods are small they contribute additional uncertainty in interpreting the double ratio results.

Interpreting the double ratios as indicators of precipitation changes due to NDCMP operations, the results indicate somewhat smaller precipitation increases than the earlier analysis by (Wise, 2005), which used a subset of the NDCMP period analyzed here and a completely different analysis approach. Our results are consistent with the increase of seasonal precipitation due to seeding in McKenzie County extrapolated by (Dennis et al., 1975) based on randomized seeding during the NDPP; however, our estimated increase again is smaller. Our results are also consistent with observed increases in individual radar-observed storm precipitation volumes due to hail suppression operations in the Calgary, Alberta, Canada area, which use similar operational procedures (Krauss and Santos, 2004) to those used in the NDCMP. The overall result offers support for a claim of modest precipitation increases in western North Dakota due to NDCMP operations designed with a primary goal of hail suppression. Additional research is needed to increase confidence in these results.

Data availability statement

The North Dakota Cloud Modification Project evaluation discussed in this study uses a quality assured, combined ARBCON and NWS COOP data sets as described in section 2. The original ARBCON and NWS COOP data sets are freely accessible and available to all researchers. All rain gauge data in the analyzed data set are openly available from University of North Dakota data repository (Tuftedal and Delene, 2020a). A software repository (https://sourceforge.net/projects/evaluationofndcmp-tuftedal2019/) contains the project's source code and workflow. Additionally, there is a software archive available (Tuftedal and Delene, 2020b).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Bloomer, Mark, Detwiler, Andrew, 1996. Implications from the North Dakota Tracer Experiment of 1993 for the Glaciogenic Seeding of Supercooled Convective Clouds to Suppress Hail. J. Weather Modif. 28 (1), 86–91.

Boe, Bruce, Stith, Jeffrey, Smith, Paul, Hirsch, Hirsch, Helsdon, John, Detwiler, Andrew, Orville, Harold, Martner, Brooks, Reinking, Roger, Meitin, Rebecca, Brown, Rodger, 1992. The North Dakota thunderstorm project: a cooperative study of high plains thunderstorms. Bull. Am. Meteorol. Soc. 73 (2), 145–160.

Braham, Roscoe, 1968. Meteorological bases for precipitation development. Bull. Am. Meteorol. Soc. 49 (4), 343–353.

Breed, Daniel, Rasmussen, Roy, Weeks, Courtney, Boe, Bruce, Deshler, Terry, 2013. Evaluating winter orographic cloud seeding: design of the wyoming weather modification pilot project (WWMPP). J. Appl. Meteorol. Climatol. 53 (2), 282–299. https://doi.org/10.1175/JAMC-D-13-0128.1.

Bruintjes, R.T., 1999. A review of cloud seeding experiments to enhance precipitation and some new prospects. Bull. Am. Meteorol. Soc. 80, 805–820. https://doi.org/10.1175/1520-0477(1999)080<0805:AROCSE>2.0.CO;2.

Bruintjes, Roelof, Salazar, Vidal, Semeniuk, Trudi, Buseck, Peter, Breed, Daniel, Gunkelman, Jim, 2012. Evaluation of hygroscopic cloud seeding flares. J. Weather Modif. 44 (1), 69–94.

Chang, K., Bench, J., Brege, M., Cantrell, W., Chandrakar, K., Ciochetto, D., Mazzoleni, C., Mazzoleni, L.R., Niedermeier, D., Shaw, R.A., 2016. A laboratory facility to study gas-aerosol-cloud interactions in a turbulent environment: the Π Chamber. Bull. Am. Meteorol. Soc. 97 (12), 2343–2358. https://doi.org/10.1175/BAMS-D-15-00203.1.

Chen, Baujun, Xiao, Hui, 2010. Silver iodide seeding impact on the microphysics and dynamics of convective clouds in the high plains. Atmospheric Res. 96 (2–3), 186–207. https://doi.org/10.1016/j.atmosres.2009.04.001.

DeFelice, T., Golden, J., Griffith, D., Woodley, W., Rosenfeld, D., Breed, D., Solak, M., Boe, B., 2014. Extra area effects of cloud seeding — an updated assessment. Atmospheric Res. 135–136, 193–203. https://doi.org/10.1016/j.atmosres.2013.08.014.

Delene, David, 2016. Suitability of North Dakota for conducting effective hygroscopic seeding. J. Weather Modif. 48, 43–67.

Delene, David, Grainger, Cedric, Kucera, Paul, Langerud, Darin, Ham, Matt, Mitchell, Robert, Kruse, Chris, 2011. The second polarimetric cloud analysis and seeding test. J. Weather Modif. 43 (1), 14–28.

DeMott, P.J., Finnegan, W.G., Grant, L.O., 1983. An application of chemical kinetic theory and methodology to characterize the ice nucleating properties of aerosols used for weather modification. J. Clim. Appl. Meteorol. 22, 1190–1203. https://doi.org/10.1175/1520-0450(1983)022<1190:AAOCKT>2.0.CO;2.

DeMott, P.J., Super, A.B., Langer, G., Rogers, D.C., McPartland, J.T., 1995. Comparative characterizations of the ice nucleus ability of AgI aerosols by three methods. J. Weather Modif. 27, 1–16.

Dennis, A.S., Miller, J.R., Cain, D.E., Schwaller, R.L., 1975. Evaluation by Monte Carlo tests of effects of cloud seeding on growing season rainfall in North Dakota. J. Appl. Meteorol. 14, 959–969. https://doi.org/10.1175/1520-0450(1975)014<0959:EBMCTO>2.0.CO;2.

French, Jeffrey, Friedrich, Katja, Tessendorf, Sarah, Rauber, Robert, Geerts, Bart, Rasmussen, Roy, Xue, Lulin, Kunkel, Melvin, Blestrud, Derek, 2018. Precipitation formation from orographic cloud seeding. Proceedings of the National Academy of Sciences 115 (6), 1168–1173. https://doi.org/10.1073/pnas.1716995115.

Gabriel, K.R., 1999. Ratio statistics for randomized experiments in precipitation stimulation. J. Appl. Meteorol. 38, 290–301.

Gatimann, L., 1891. Method of producing rain-fall. US Patent 462,795, filed July 16,1891, and issued November 10, 1891.

He, X., Guan, H., Zhang, X., Simmons, C., 2014. A wavelet-based multiple linear regression model for forecasting monthly rainfall. Int. J. Climatol. 34, 1898–1912. https://doi.org/10.1002/joc.3809.

Hesterberg, T., Monaghan, S., Moore, D., Clipson, A., Epstein, R., 2005. Bootstrap Methods and Permutation Tests. W. H. Freeman and Company.

Johnson, Howard, 1985. An Evaluation of the North Dakota Cloud Modification Project: 1976–1982. A Final Report to the North Dakota Weather Modification Board.

Karacostas, T., Kartsios, S., Pytharoulis, I., Tegoulias, I., Bampzelis, D., 2018. Observations and modelling of the characteristics of convective activity related to a potential rain enhancement program in central Greece. Atmospheric Res. 208, 218–228. https://doi.org/10.1016/j.atmosres.2017.08.014.

Krauss, Terrence, Santos, Jorge Ruben, 2004. Exploratory analysis of the effect of hail suppression operations on precipitation in Alberta. Atmospheric Res. 71, 35–50. https://doi.org/10.1016/j.atmosres.2004.03.004.

Lane, D., 2003. Online Statistics Eduation: A Multimedia Course of Study. Proceedings of ED-MEDIA 2003–World Conference on Educational Multimedia, Hypermedia & Telecommunications. Association for the Advancement of Computing in Education (AACE), pp. 1317–1320.

Langerud, D., Gilstad, A., 2003. Comparative Analysis of the Atmospheric Resource Board Cooperative Observer Network with the National Weather Service Rain Gauge Network. North Dakota Atmospheric Resource Board.

Langerud, Darin, Moen, Paul, 1998. An Update on the North Dakota Cloud Modification Project. J. Weather Modif. 30 (1), 85–90.

Levin, Zev, Halfon, Noam, Alpert, Pinhas, 2010. Reassessment of rain enhancement experiments and operations in Israel including synoptic considerations. Atmospheric Res. 97 (4), 513–525. https://doi.org/10.1016/j.atmosres.2010.06.011.

List, R., Gabriel, K.R., Silverman, B.A., Levin, Z., Karacostas, T., 1999. The rain enhancement experiment in Puglia, Italy: statistical evaluation. J. Appl. Meteorol. 38, 281–289. https://doi.org/10.1175/1520-0450(1999)038<0281:TREEIP>2.0.CO;2.

Liu, Weibo, Li, Xingong, 2016. Life Cycle Characteristics of Warm-Season Severe Thunderstorms in Central United States from 2010 to 2014. Climate, https://doi.org/10.3390/cli4030045.

Miller, J.R., Fuhs, M.J., 1987. Results of hail suppression efforts in North Dakota as shown by Crop Hail Insurance Data. J. Weather Modif. 19, 45–49.

Muralikrishna, I.V., Manickam, V., Bhardwaj, S.S., Peddj, H., Rao, A.P., 2009. Design and evaluation of hygroscopic seeding operations in Andhra Pradesh, India. Journal of Weather Modification 41 (1), 135–143.

Schaefer, V.J., 1968. The early history of weather modification. Bull. Am. Meteorol. Soc. 49, 337–342. https://doi.org/10.1175/1520-0477-49.4.337.

Schneider, M.D., Langerud, D., 2011. Operational improvements on the North Dakota cloud modification project. J. Weather Modif. 43 (1), 84–88.

Shier, Rosie, 2004. Statistics: 2.3 The Mann-Whitney U Test. Mathematics Learning Support Centre.

Silverman, B.A., Koshio Rogers, L., Dahl, D., 1981. On the sampling variance of raingage networks. J. Appl. Meteorol. 20, 1468–1478. https://doi.org/10.1175/1520-0450(1981)020<1468:OTSVOR>2.0.CO;2.

Smith, P.L., Mielke Jr., P.W., Kopp, F.J., 2004. Exploratory Analysis of Climatic Raingage Data for evidence of Effects of the North Dakota Cloud Modification Project on Rainfall in the Target Area (No. SDSMT/IAS/R04-01). North Dakota Atmospheric Resource Board.

Tajiri, T., Yamashita, K., Murakami, M., Saito, A., Kusunoki, K., Orikasa, N., Lilie, L., 2013. A Novel Adiabatic-Expansion-Type Cloud simulation Chamber. J. Meteorol. Soc. Jpn. Ser II 91, 687–704. https://doi.org/10.2151/jmsj.2013-509.

Tuftedal, Delene, D., 2020a. Precipitation Evaluation of the North Dakota Cloud Modification Project (NDCMP) Using Rain Gauge Observations. Datasets. https://doi.org/10.31356/data017.

Tuftedal, Delene, D., 2020b. Evaluation of the North Dakota Cloud Modification Project (NDCMP) [WWW Document]. Zenodo. URL. https://doi.org/10.31356/data017.

Weather Modification International, 2018. North Dakota Cloud Modification Project 2018 Final Operations Report. North Dakota Atmospheric Resource Board.

Wise, E., 2005. Precipitation Evaluation of the North Dakota Cloud Modification Project (NDCMP). University of North Dakota, Grand Forks, North Dakota.

Woodley, W.L., Rosenfeld, D., 2004. The Development and Testing of a New Method to Evaluate the Operational Cloud-Seeding Programs in Texas. J. Appl. Meteorol. Climatol. 43, 249–263. https://doi.org/10.1175/1520-0450(2004)043<0249:TDATOA>2.0.CO;2.

Zhang, A., Shi, H., Li, T., Fu, X., 2017. A bootstrap method to estimate the influence of rainfall spatial uncertainty in hydrological simulations. Hydrol. Earth Syst. Sci. Discuss. 1–31 https://doi.org/10.5194/hess-2017-273.

Zipori, Assaf, Rosenfeld, Danie, Shpund, Jacob, Steinberg, David, Erel, Yigal, 2012. Targeting and impacts of AgI cloud seeding based on rain chemical composition and cloud top phase characterization. Atmospheric Res. 114, 119–130. https://doi.org/10.1016/j.atmosres.2012.05.023.