PRECIPITATION EVALUATION OF THE NORTH DAKOTA CLOUD MODIFICATION PROJECT (NDCMP)

by

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

Chairperson

This thesis meets the standards for appearance, conforms to the style and format requirements of the Graduate School of the University of North Dakota, and is hereby approved.

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ABSTRACT

This paper focuses on the evaluation of the North Dakota Cloud Modification Project (NDCMP). The goal of the research was to study the effects of cloud seeding on precipitation generation in the target and downwind regions of the two cloud seeding districts in western North Dakota. The Atmospheric Resource Board Cooperative Observer Network (ARBCON) rain gauge data were used.

Rain gauge data were categorized into target, downwind, and control regions with respect to each seeding district. Specifically, rain gauges adjacent to the target regions that were not downwind of each district, were used as the control regions. Precipitation was evaluated on a monthly basis. The downwind/control regions for each month were determined by observing radar-derived storm tracks from 1999 to 2002. Regions were created based on predominant storm flow regimes determined by radar. Two main wind flow regimes, northwesterly or southwesterly flow, were used. The daily flow regimes were based on the NCEP/NCAR Reanalysis wind data. Results from the analysis of 27 years of NDCMP data indicated that seeding had a positive effect on increasing precipitation amounts in both the target and downwind regions.

The results indicate that, on average, precipitation amounts increased by 6-9%. A description of the methodology and detailed results are illustrated in this report. A Monte Carlo test showed that the results were significant in two cases for total season rainfall: both the target and downwind comparison with the control region for District II with a

southwest flow. The target region received 8% more rainfall than the control, and the downwind region received 13% more rainfall than the control region.

CHAPTER 1

INTRODUCTION

The North Dakota Cloud Modification Project (NDCMP) is a non-randomized summertime (June, July, and August) cloud seeding program in western North Dakota. The NDCMP has two objectives: to suppress hail damage on crops and to increase precipitation during the growing season. This study evaluated the success of increasing summertime precipitation.

Cloud seeding in North Dakota started in the 1950's by using ground-based generators to seed clouds. In the late 1950's, there were several years when farmers experienced significant or total crop loss due to hail damage. In the early 1960's as a response to the crop losses, two pilots and a farmer in Bowman County, North Dakota founded Weather Modification Incorporated (WMI) becoming the first in the state to use aircraft to seed clouds. Their primary goal was to suppress hail, but a secondary objective of increasing rainfall was quickly added. In the mid 1960's, radar was added to increase the lead-time in identifying ideal clouds for seeding. In 1976, the state of North Dakota took over all cloud seeding operations in the state and provided meteorological support and contracting for cloud seeding equipment.

This study evaluates the NDCMP success of enhancing precipitation from 1977 to 2003. During this period the NDCMP seeded clouds in two districts located in western North Dakota (Fig. 1). In the two districts, counties or portions of counties have joined or left the cloud seeding project during the 27-year period. The counties and years they participated in the project can be seen in Table 1. In this study, the counties that participated in the NDCMP during the longest period, ideally the whole period, were used as target (seeded) regions. For District I, four counties participated in cloud seeding during the period. Only Bowman County participated in the project for the full 27-year period. Slope County participated for 22-years, which was considered a large enough data set to show the effects of cloud seeding. Therefore, a 22-year (1977-1998) evaluation was conducted on District I using Slope and Bowman counties as target regions. For District II, three of the five counties participated for the whole period. The other two counties participated for less than half of the period, so McKenzie, Mountrail, and Ward counties were used as the target region.

Table 1. Counties and dates of participation in the NDCMP from 1977 to 2003.

Counties	District	Years Participated
Adams	I	1977-1980
Bowman	I	1977-2003
Slope	I	1977-1998
Hettinger	I	1977-1988
McKenzie	II	1977-2003
McLean	II	1977-1984
Mountrail	II	1977-2003
Ward	II	1977-2003
Williams	II	1997-2003

There are previous evaluations on the success of both goals of the NDCMP. One evaluation was conducted on a state-operated project in South Dakota, which operated under the same principles as the NDCMP, and included one year of cloud seeding in North Dakota in 1976. The results of the study indicated an increase in seasonal rainfall of 5 to 10% due to cloud seeding (Pellett et al., 1977). Another evaluation of cloud seeding in North Dakota was conducted by Eddy et al. (1979), and the findings showed indications of a 7% increase in daily rainfall due to cloud seeding.

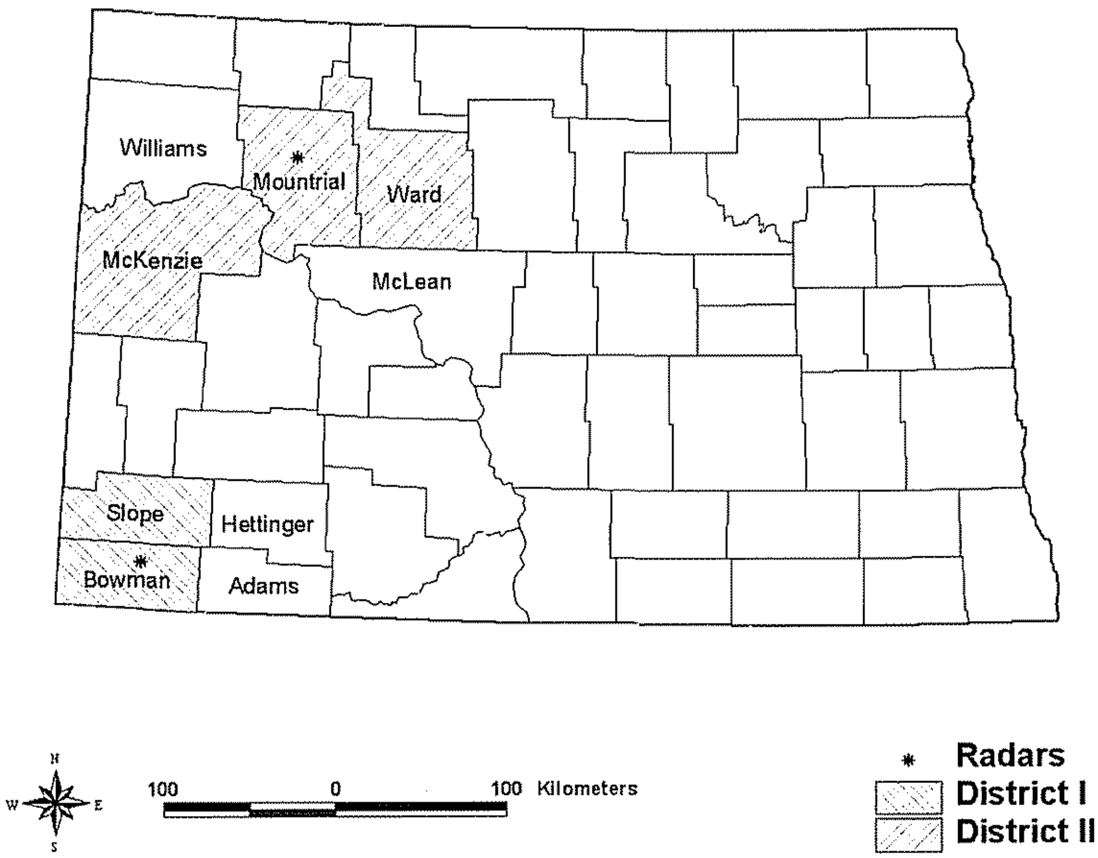


Figure 1. The seeded regions for the NDCMP that have been seeded for the entire period from 1977 to 2003 for District II and from 1977 to 1998 for District I.

Eddy (1981) conducted an evaluation in which trajectories were used to determine the downwind areas from the seeding locations. Eddy et al. (1982) conducted another evaluation on the NDCMP using an analysis of covariance as an analysis tool. These two studies each indicated a significant increase in precipitation in and downwind of the seeding regions; however, there were some problems with the results. In these studies, the gauges used as the seeded category were only gauges seeded on the given day, while the gauges used as the unseeded category were all of the other gauges used that were not seeded. When seeding for hail suppression, usually the most intense storms are seeded, which then would be included in the seeded category; the control included the remaining storm events (Eddy et al., 1982). Therefore, the significant increase in precipitation could largely be due to the difference in intensity of the storms between the seed group and control group.

A summertime precipitation enhancement evaluation of the NDCMP from 1976 to 1982 was conducted by Johnson (1985). This study showed weak evidence of an overall increase of rainfall in and downwind of the target with respect to the control. The results were consistent with that of earlier results, showing that seeding for hail suppression in North Dakota likely does increase rainfall. However, no evidence of the effectiveness of seeding for rainfall enhancement was found.

In the current study, a Monte Carlo test was applied to the difference in rainfall between the control and the target and downwind regions. A Monte Carlo test is a non-parametric method to estimate the statistical significance of results. It is often used when traditional significance tests are not feasible. The purpose of this test was to determine if the differences between the target-control and the downwind-control were significant which could infer whether the effects were due to seeding or not. There was a previous evaluation that used a Monte Carlo test in evaluating the effects of cloud seeding on rainfall in North Dakota. The evaluation was conducted on a randomized cloud seeding experiment conducted in 1975, and an increase in precipitation in seeded regions was found. The conclusions of the evaluation stated that it was likely that a calculated increase in rainfall in seeded regions was due in part to enhanced cloud growth induced by seeding (Dennis et al., 1975).

The evaluation in this thesis was quantified by using the North Dakota Atmospheric Research Board Cooperative Observer Network (ND ARBCON) rain gauge data. The ND ARBCON is a statewide network comprised of volunteers that started in 1977 and is still operational today. The ND ARBCON data records daily rainfall amounts and hail that occurred at each observer location from April to September, which is considered the warm season in North Dakota. If snow does fall during the time the ND ARBCON is operational, no measurement is recorded for that day due to the inability to determine the liquid water content of snow.

Previous studies used the National Weather Service (NWS) rain gauges to evaluate rainfall. The ND ARBCON data is a denser network than the NWS rain gauge network. The hypothesis was that the denser ND ARBCON data may be able to better identify the effects of seeding in the NDCMP. Rain gauges are point targets that only record the rainfall amount at an exact location. Summertime rainfall is usually convective and not uniform across an area, so rainfall amounts can vary greatly over short distances. For example, there are times when storms or showers can barely miss a gauge, but produce rainfall over a good portion of the area that the gauge represents. By having more gauges in an area, the likelihood of at least one of the gauges recording precipitation increases.

The quality of the ND ARBCON rain gauge data must be factored in the study. A comparative analysis of the ND ARBCON rain gauge data and the NWS rain gauge network data from 1977 to 1999 was completed by the North Dakota Atmospheric Resource Board (NDARB) (Krajewski et al., 2002). The two networks were compared on an annual, multi-annual, and monthly time period. The annual and multi-annual comparison was performed using ND ARBCON gauges within a 10 km radius of a NWS gauge on a given year where the criteria resulted in at least two ND ARBCON gauges for every NWS gauge. The monthly comparisons used ND ARBCON gauges within a 5 km radius of a NWS gauge on a given year, which again yielded at least two ND ARBCON gauges for every NWS gauge. A daily comparison was not conducted because of differences between the two networks; primarily in reporting times and procedures. These differences were not as significant at larger time scales. The comparison showed a good agreement between the two networks on a monthly, annual, and multi-annual time scale, with the best agreement found at annual and multi-annual times (Krajewski et al., 2002). The multi-annual comparison included all the years in the study by Krajewski et al. (2002).

The statistics used in the present evaluation were based on a ratio test for evaluating rainfall enhancement for cloud seeding projects defined by Gabriel (1999, 2002). These tests show the difference between the target/downwind regions, (the notation of target/downwind in this paper means target or downwind), and their corresponding control regions.

There are two distinct summertime wind patterns in western North Dakota: a southwesterly flow and a northwesterly flow, therefore, this study conducted an evaluation for both flow regimes. There was a southwest and a northwest target region with a downwind and a control region for each district. As shown in Fig. 1, the two districts were on the western border of the state. Ideally, the control gauges would be located to the west of target regions for westerly winds. However, this was impossible because the rain gauge locations were only in North Dakota and so a control region to the west could not be used. Instead, the control regions were located to the south and north of the target regions. Each district and wind flow regime was tested separately. The NDCMP operates during the months of June, July, and August. This study conducted an evaluation for each month and a seasonal evaluation for both flow regimes and districts.

The data used in conducting the results are discussed in Chapter 2. The methodology stating how the study was conducted is explained in Chapter 3. The results of the rainfall evaluation are discussed in Chapter 4. Conclusions and discussion of future studies are provided in Chapter 5.

CHAPTER 2

DATA

Since this study focused on evaluating precipitation using rain gauge data., the ND ARBCON rain gauge data were used to quantify precipitation amounts between the target/downwind regions and their corresponding control regions. Storm track data from NDCMP radar Thunderstorm, Identification, and Tracking, Analysis, and Nowcasting (TITAN) (Dixon and Wiener 1993) software were used in determining the mean storm flow for seeded days. Storm track data were utilized to determine control and downwind regions for the dominant southwest or northwest flow regimes. Also, wind data from the National Centers for Environmental Prediction (NCEP) National Center for Atmospheric Research (NCAR) Reanalysis data (Kalnay et al. 1996) were utilized to determine which flow regime was used on a given day.

ND ARBCON

The ND ARBCON network of rain gauges varied from year to year but were generally distributed similarly to the rain gauge distribution shown in Fig. 2. The number of gauges in the network ranged from 505 in 1977, to over 900 in the late 1980's. The rain gauges used in the ND ARBCON were wedge-shaped (Fig. 3) in design. The gauges record rainfall amounts to the nearest hundredth of an inch to one inch of rainfall and then to the nearest five hundredths of an inch to a maximum of six inches.

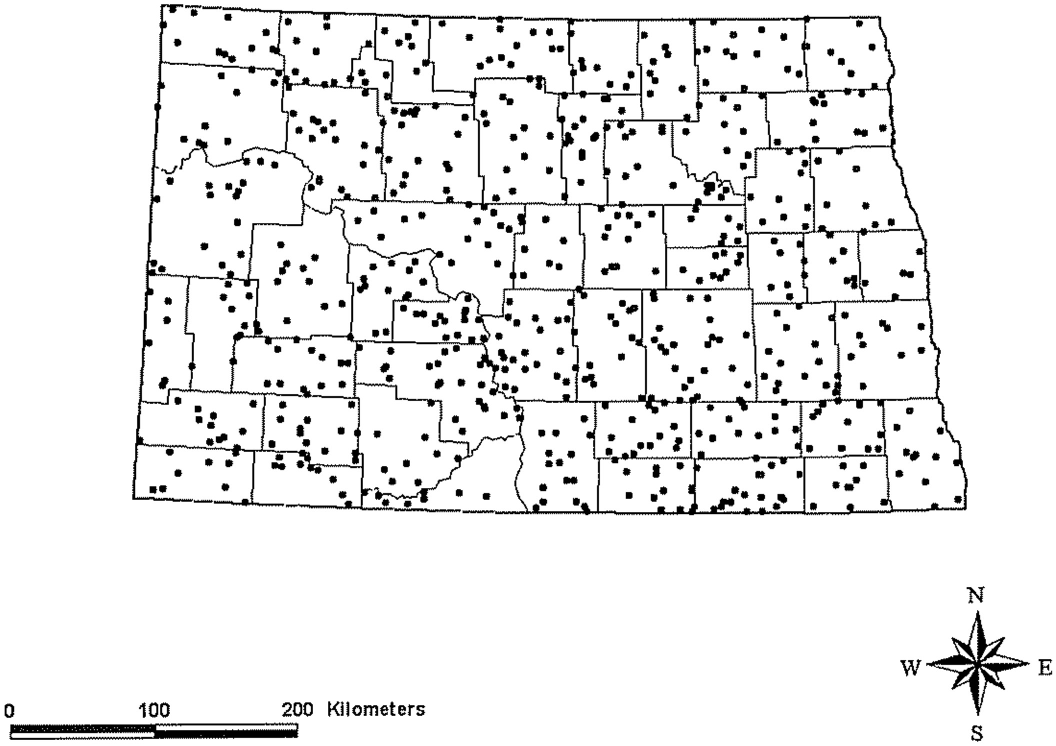


Figure 2. June 2002 ND ARBCON rain gauge locations.

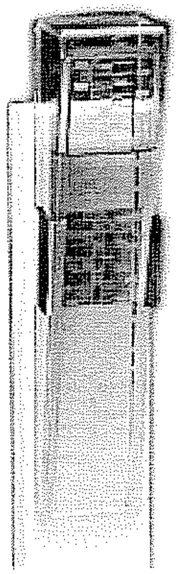


Figure 3. Type of rain gauge used in the ND ARBCON.

The volunteer observers of the ND ARBCON were given a rain gauge and instructions on where to locate it and how to measure and record the daily rainfall amounts. The observers recorded the rainfall amount once a day on a standard form at 0800 AM local time. If no rain fell on a given day, the observers recorded a rainfall amount of 0.0 inches. If they were unable to take a reading on a day, such as when they were not at home, they left the rainfall amount for that day blank. The rainfall amount for a gauge on a given day was recorded on the day it was measured, and since the gauge was checked at 0800 AM every day, the majority of the rainfall would have actually occurred on the previous day because most summertime rainfall in western North Dakota occurs in the afternoon and evening hours.

There could have been errors when observations were made at non-standard times. If precipitation occurred in the afternoon or evening, observations recorded near 0800 AM should have minimum timing errors. However, if a substantial number of observers waited until the afternoon or evening hours to make their observations, or the precipitation occurred in the mornings, this could have introduced unknown errors into the analysis. It was assumed that most observers infrequently made errors in recording the observed rainfall amounts in the gauges. There were cases found when an observer recorded the rainfall amount on the wrong day. Corrections were made to known occurrences, but this type of error could only be discovered when two gauges were located in very close proximity to each other. When the gauges were located farther apart, it was harder to detect. Summertime precipitation can be spatially variable over relatively short distances, therefore, it is feasible that one gauge would receive rainfall but an adjacent gauge would not. More information, such as radar data, would be necessary to determine if a gauge was incorrectly recorded. The NDARB conducted quality control on the ND ARBCON rain gauge data and tried to correct this problem for cases where the error was obvious. For this study, unless an obvious error was found, the rainfall amounts were used exactly how they were recorded. It was assumed that this problem only occurred a negligible number of times with respect to the number of days and gauges.

At the end of the month, the volunteers mailed their forms to the NDARB office. The NDARB entered the data into their computer system manually, so if any gauge data looked suspect, it was flagged until the data could be confirmed. There was no other extensive quality control to the rain gauge data.

Flight Reports

When NDCMP planes were flown, the pilots filled out a flight report. The contents of the reports included the time the aircraft took off and landed, the purpose of the flight, and the time and locations the aircraft seeded clouds. The flight reports from 1998 to 2002 were obtained from the NDCMP, because they coincided with the use of the TITAN radar software implemented by the NDCMP. Due to insufficient radar data for 1998 (see discussion in following section), only the flight reports from 1999 to 2002 were used to determine seeded days and locations. By going through these reports, the days of active seeding were cataloged.

TITAN Storm Tracks

The NDARB uses two Weather Surveillance Radar-1974 C band (WSR-74C) 5-cm weather radars, located at Bowman and Stanley Airports for operational support of the NDCMP. Bowman Airport is located in Bowman County in District I, and the Stanley

Airport is in Mountrail County in District II. The radars operate 24 hours a day, seven days a week during the NDCMP operational period of June through August. The NDARB hires operational and intern meteorologists to operate the radars to assist in directing aircraft to suitable clouds for seeding. The radars have the TITAN (Dixon and Wiener 1993) systems to display the data.

In 1998, the NDCMP implemented the TITAN radar software to help determine which clouds were seeded. TITAN tracks the movement of cells and records several elements of the cell (e.g., the storm number, the date and time a cell is tracked, and how long it is tracked). Also, other parameters that are recorded include the x and y coordinates of the cell, the height above ground level of the reflectivity, and the volume centroid. The maximum and mean reflectivities are recorded along with the height of the maximum reflectivity. Other elements recorded are the height of cloud base and cloud top, along with the volume, mean area, and mass of the storm. TITAN also calculates and records precipitation flux, precipitation area, vorticity, speed and direction of a cell tracked in the storm tracks. Also recorded are volume, precipitation flux, cloud top, mass and reflectivity per time duration. For this research, only the speed and direction are used to calculate the mean storm flow for seeded days.

The storm tracking is done by considering storms to be distinct three-dimensional entities that can be identified with physically based properties that can be computed. These entities can be tracked by matching storms at one time to their counterparts at a later time (Dixon and Wiener 1993). This is referred to as "centroid tracking" (Austin and Bellon 1982). The advantage of this approach is that it makes for a more complete use of the information available. If correctly measured, three-dimensional centroid tracking should produce a better forecast than a two-dimensional data based technique (Dixon and Wiener 1993).

The TITAN tracking software for the NDCMP was set up to track all cells that reached a reflectivity value of 30 dBZ or greater. When a cell reaches a 30 dBZ or greater reflectivity value in a radar scan, and still has a 30 dBZ or greater reflectivity value in the next scan, then TITAN calculates the speed and direction of the cell centroids. The TITAN tracking algorithm has some limitations. One drawback is that it only tracks storms with a reflectivity equal to or greater than 30 dBZ. If only a few cells reach the threshold of 30 dBZ in a day, there would not be adequate data to accurately determine the storm flow for the given day. Light precipitation events having reflectivities less than 30 dBZ would not be tracked by TITAN. On days where seeding took place, there would have likely been cells that met the threshold to be tracked by TITAN. Hail producing cells are stronger in intensity, therefore, the reflectivity is usually 30 dBZ or greater. Another drawback of the TITAN algorithm is that it can falsely identify new cell growth to be an old cell that weakened to less than 30 dBZ in the next radar scan. This effect provides an incorrect speed and direction. Also, when the tracking data identifies two cells as one, the retrieved track could show the movement of a cell to be faster or slower than its actual speed. If only a few cells develop during the day, a large uncertainty could occur in the mean storm flow because of the small sample size.

The TITAN storm tracks data was used to determine the mean storm flow for all days seeded in the NDCMP from 1999 to 2002. The 1998 radar dataset had a significant portion of missing days, and therefore, was excluded from the analysis. Also, there were days in 1999 to 2002 when there was missing data and those days were excluded from the analysis as well. The 1999 to 2002 TITAN storm tracks data were used for both the Bowman radar and the Stanley radar to define downwind and control regions, and to determine which pressure level of the NCEP/NCAR reanalysis data (see next section) best represents the storm flow for seeded days. This was then used to infer mean storm track movement for years without TITAN storm track data.

NCEP/NCAR Reanalysis Data

The NCEP/NCAR Reanalysis Project is an effort to reanalyze historical data using state-of-the-art models. The NCEP/NCAR reanalysis uses a frozen state-of-the-art global data assimilation system and a database from 1947 to the present that is as complete as possible (Kalnay et al. 1996). There are several types of data available from the reanalysis, including: pressure level data, surface data, surface flux data, other flux data, tropopause level data, and T62 Spectral data. In each data type, there are several fields of data. All the data NCEP/NCAR reanalysis data can be obtained at http://www.cdc.noaa.gov/cdc/data.ncep.reanalysis.html.

Wind information was needed for every day from 1977 to 2003 for June, July, and August. Since the storm tracks data was limited to a four-year record, NCEP/NCAR reanalysis data was used to estimate wind direction and speed estimates for all seeded years.

In this research project, the mean storm flow was important, so only data at various constant pressure levels were used. The data fields that were classified as pressure data include: air temperature, geopotential height, relative humidity, specific humidity, vertical velocity (Omega), U-wind, and V-wind. The data had a spatial coverage of 2.5-

degree latitude x 2.5-degree longitude global grid with 144x73 points, and a temporal coverage of January 1948 to the present with output every six hours. The data was available for all the following pressure levels in the atmosphere: 1000, 925, 850, 700, 600, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20, and 10 mb. In this project only the u (W-E) and v (N-S) wind components for the 700, 600, and 500 mb constant pressure levels were used, because these levels are commonly the steering levels for storms. Combinations of times were used to find the best representation of the mean storm flow. How the combinations of times were calculated will be discussed in Chapter 3. The wind data used was from the closest grid point to the center of each District. NCEP/NCAR reanalysis Data from 1977 to 2003 for all 6-hour time periods were used.

Climate Data

The climatological distribution of precipitation is not uniform across North Dakota, with a general increase from the northwest to the southeast across the state. Precipitation data for 1931 to 1960 were used to determine the natural variation of rainfall amounts. The 1931 to 1960 climate data were chosen over the 1961 to 1990 climate data because seeding was limited to only a few years during the 1950's. The 1961 to 1990 North Dakota climatic precipitation values include the possible effects of seeding and could not be used to determine the natural variability of precipitation. The climate data for June, July, and August were used (Fig. 4, 5, and 6 respectively), and Fig. 7 shows the gauge locations. It is seen that from 1930 to 1961 the southeast portions of the state received the most rainfall and the northwest portion the least amount of rainfall for these three months. There were local maxima or minima, but overall the general pattern shows an increase from the northwest to the southeast.

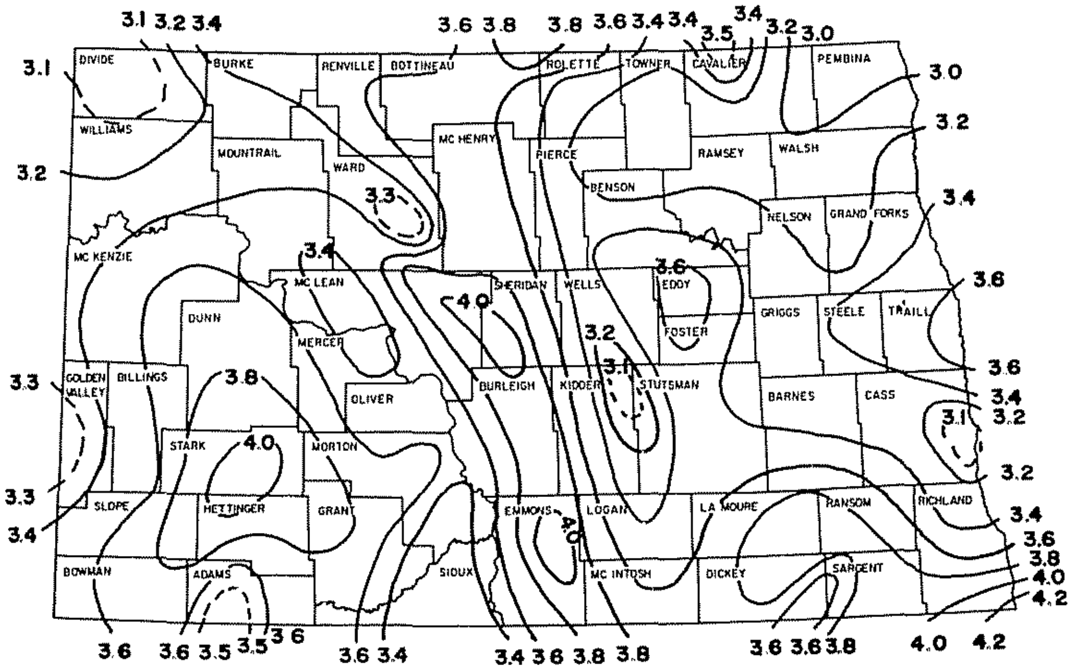


Figure 4. June 1931 to 1960 mean precipitation in inches for North Dakota (Jensen 1972).

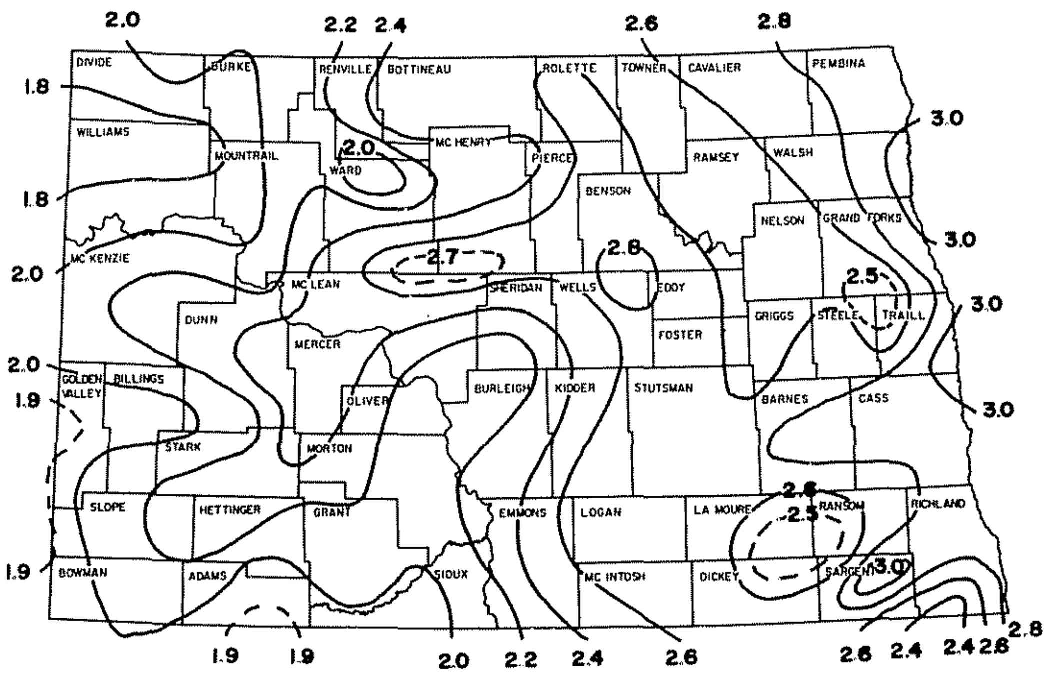


Figure 5. July 1931 to 1960 mean precipitation in inches for North Dakota (Jensen 1972).

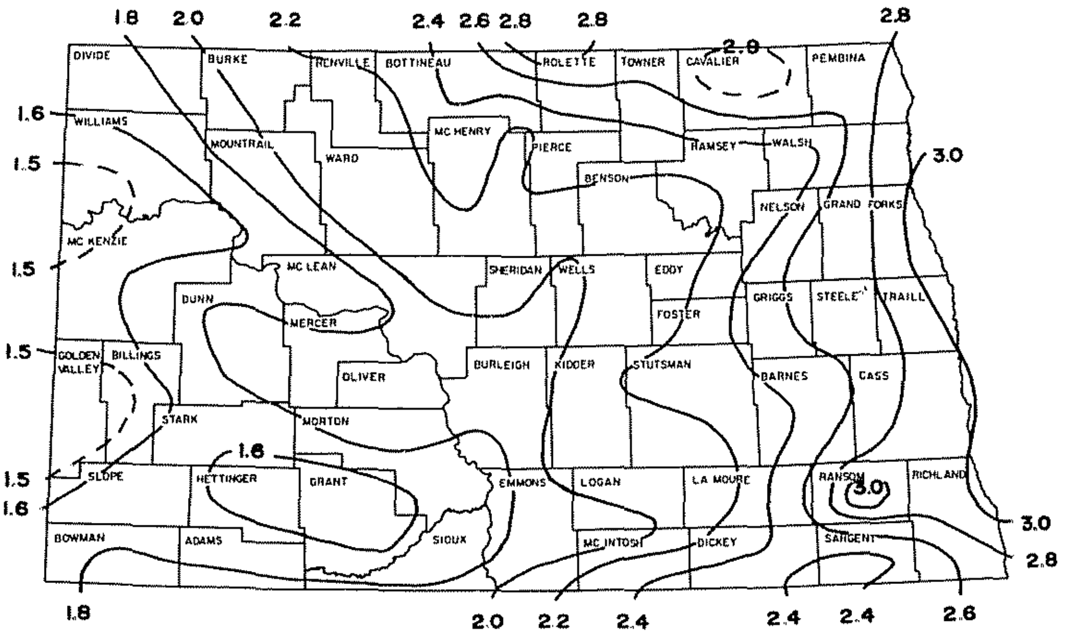


Figure 6. August 1931 to 1960 mean precipitation in inches for North Dakota (Jensen 1972).

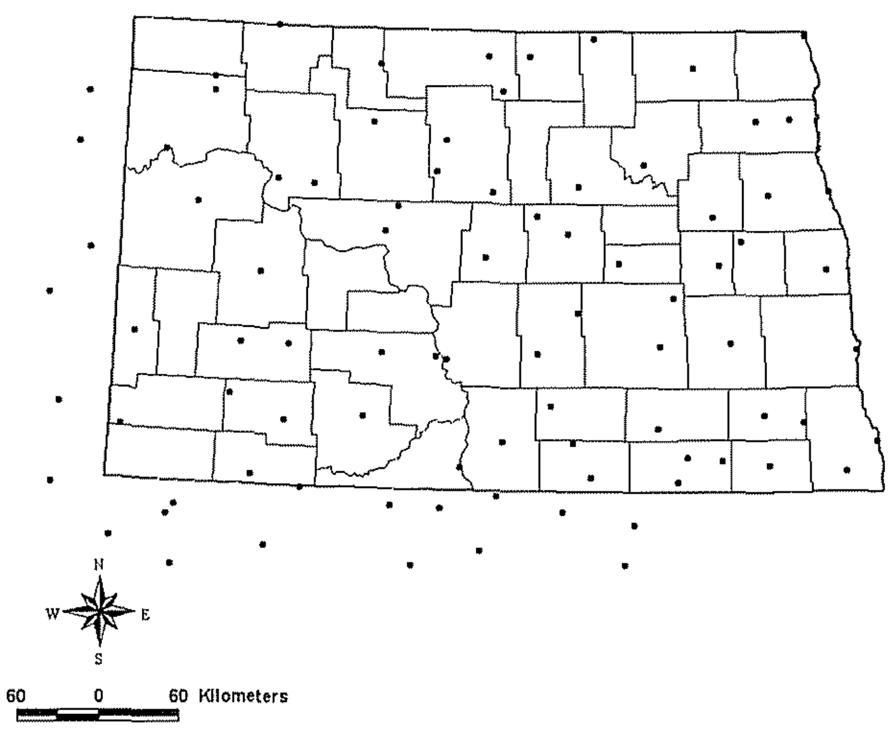


Figure 7. North Dakota 1931 to 1960 climate rain gauge locations.

It is noted that the 1931 to 1960 climate data may not be representative of the current climate conditions. The 1931 to 1960 precipitation recorded for western North Dakota included two periods of significant drought conditions. However, the amount of precipitation that ND received in that time period was not crucial for this study. What had to remain the same were the climatic ratios of rainfall between the control, downwind, and target regions. The climate data were used to calculate ratios between the downwind or target regions and the control regions to account for natural variations in rainfall between the different regions. For this research, it was assumed that the ratios between the different regions in the 1931 to 1960 climate data were representative of the ratios during the study period without the effects of seeding. This assumption could not be tested because of the seeding activities in North Dakota. Because seeding took place from 1960 to the present, any data used after 1960 were biased by the effects of seeding. However, it is recognized that this assumption could contribute to the uncertainty in the analysis.

CHAPTER 3

METHODOLOGY

Storm Flow

The downwind and control regions were determined by finding the mean storm direction of movement, or "flow", on days when clouds were seeded. The TITAN software storm tracks data was used to determine the storm flow for all days when seeding took place from 1999 to 2002. For each day a u and v component was calculated from the speed and direction for every cell. The angles created from the mean u and v track components were used to determine the mean storm flow for that day. The daily storm flows were then sorted into northwesterly and southwesterly flows. A northwest and southwest mean storm flow for the seeded days was calculated from the daily storm flows for both districts.

Between 1999 and 2002, there were 95 days seeded in District I and 147 days seeded in District II. Not all the days had storm track data, or a significant (five or more) number of storm tracks. For District I, only 84 of 95 seeded days had significant storm track data and for District II 142 of 147 seeded days had significant storm track data available.

For every day seeded, mean storm flows were calculated for a northwest and southwest flow for both districts along with a total mean storm flow. The mean southwest storm flow direction was 60° for District I, and the southwest mean storm flow direction for District II was 61°. The northwest mean storm flow for District I and District II was 112°.

The next step was to determine the range of storm flow directions that included the majority of the seeded days for each flow regime. This range was used to determine the downwind regions for both districts and flow regimes. For each flow regime, the limits were calculated to include at least 90% of the seeded days. The northwest flow range was 91° to 142°, which included 94% of the seeded days for District I and 90% of the seeded days for District II. By choosing 90% this should have included the majority of the days seeded without including the outliers of storm flow direction for seeded days.

It was calculated that 90% of the seeded days daily storm flows was a southwest flow for both districts fell within the range of 25° to 89°. However, defining the downwind regions by this range would have left a very small area for the control region with an insignificant number of gauges to conduct the study. Therefore, the range of 45° to 89° was used in order to have a significant number of gauges in the control regions. This range included 75% of the days seeded.

Figure 8 shows the daily storm flows and the total, southwest, and northwest storm flow means for Districts I and II. In these figures, the storm track vectors in quadrant 1 included storm flows from the southwest, and storm track vectors in quadrant 2 included storm flows from the northwest. The dashed line represents the mean southwest storm flow and the dotted line represents the mean northwest storm flow.

It is seen in Fig. 8 that there were more seeded days in District II than District I. The District II target region was larger in area than District I (Fig. 1), which led to more opportunities for suitable clouds for seeding. According to the storm tracks data, there were only a few days that were seeded when the storm flow was from the east. These days are located in quadrant 3 and 4 in Fig. 8.

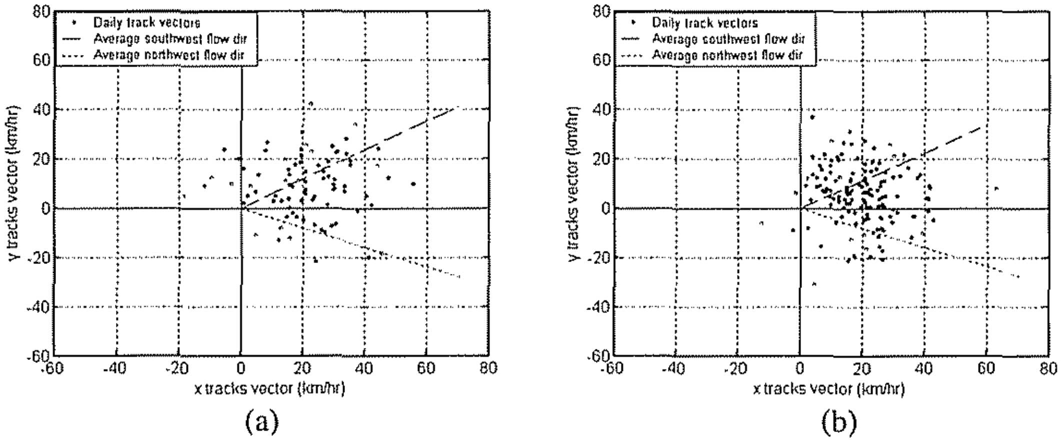
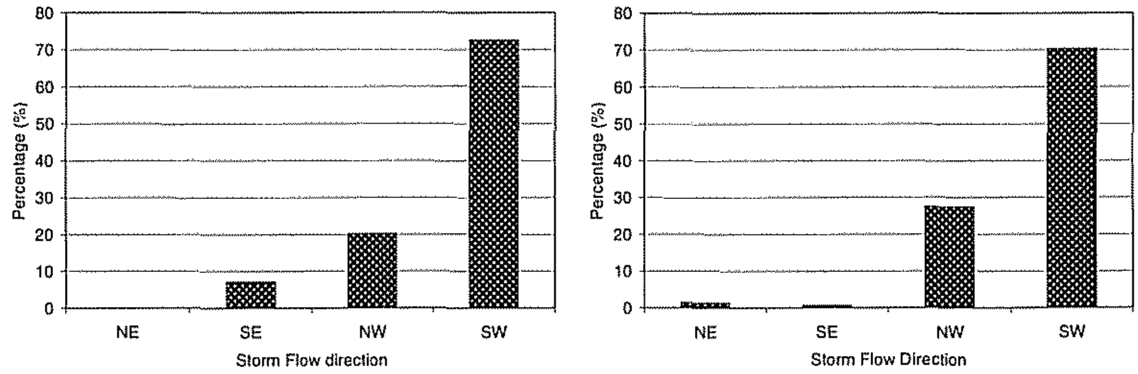


Figure 8. Daily mean storm flow for seeded days from 1999 to 2003 for a) District I and b) District II.

Figure 9 shows the frequency distribution of the daily wind direction for District I and II. *NE* represents winds from the northeast, *SE* represents winds from the southeast, *NW* represents winds from the northwest, and *SW* represents winds from the southwest. Over 90% of the days seeded had flow out of the west for both districts, with 70% or more days seeded when the flow was from the southwest. For District I, there were 84 days seeded from 1999 to 2002, and 143 for District II. Although the majority of days seeded had southwest flow, there were still a sufficient number of days seeded under northwest flow to justify the use of the two wind flow regimes.

The daily number of TITAN storm tracks varied. As mentioned in Chapter 2, there was the possibility that TITAN could have incorrectly calculated the direction of a storm. If there were a large number of cells tracked on a day, and only a small number had errors, the effect of these errors on the daily storm flow would have been minimal. It was also possible that having more cells tracked on a day would lead to more errors in the storm tracks being averaged out by more storm tracks that were accurately tracked.

However, it was thought that by having a larger number of storm tracks on a day would lead to more correct tracks and average out the incorrect storm tracks.



(a) (b)

Figure 9. Frequency distribution of daily mean storm flow direction for days seeded in western North Dakota from 1999 to 2002 a) District I b) District II.

Regions

Based on the directional range of the daily storm tracks calculated for each district and flow regime, the downwind regions were defined. The areas that were not in the downwind regions but were adjacent to the target and downwind regions were defined as the control regions. The downwind regions extended from the target region to 75 km away. The 75 km range was an arbitrary distance decided before the research was conducted, and was chosen because it was thought to be a large enough distance to include the possible effects of seeding. The control regions were then defined as the areas relatively close to the target regions that were outside of the downwind regions. These were located adjacent to and upwind of the target areas.

Ideally, all the regions should be the same size by area and number of gauges. However, the target regions were set in size and could not be modified. Additional constraints were that the target regions were located on the western (Montana) border of North Dakota and only days when the wind was from the west (northwest or southwest) were used. Therefore, since there were no ND ARBCON gauges located in Montana, the size of the control regions was limited. Figure 10 and 11 shows the southwest flow and northwest flow regions respectively.

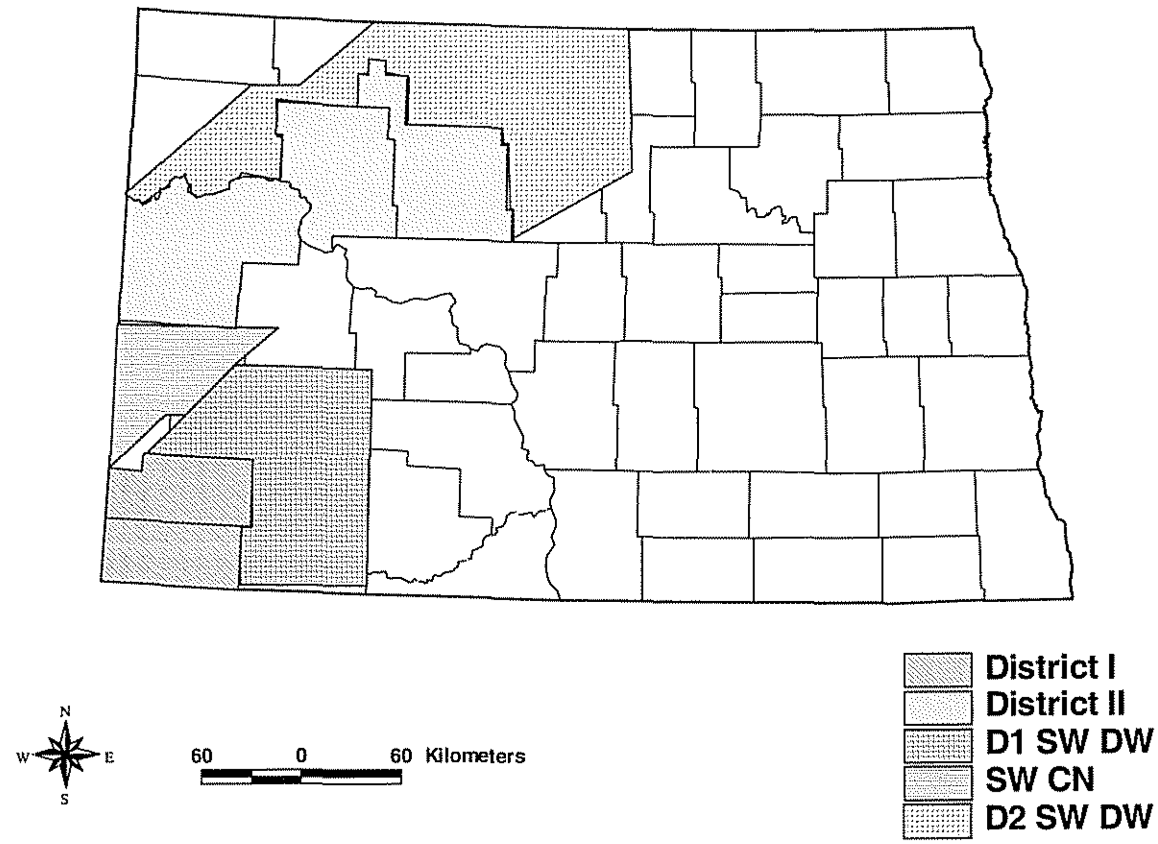


Figure 10. Southwest flow target, downwind, and control regions for Districts I and II.

For a southwest flow, both Districts I and II shared a control region. The downwind regions for a southwest flow extended from the target regions at an angle of 45° to 89° out to 75 km, but the Canadian border kept portions of the region from extending out to 75 km. The control region was defined by the area bounded by the 45° angles and the Montana-North Dakota border. The southeast corner of the District II downwind region did not extent to 89°, because it was determined that a very small portion of the target region would have to been seeded in order to affect this region. The regions for a northwest flow for both Districts I and II can be seen in Fig. 11. Again, a downwind region for a northwest flow was not used for District I because the majority of the study area would have been located in South Dakota, outside the ND ARBCON.

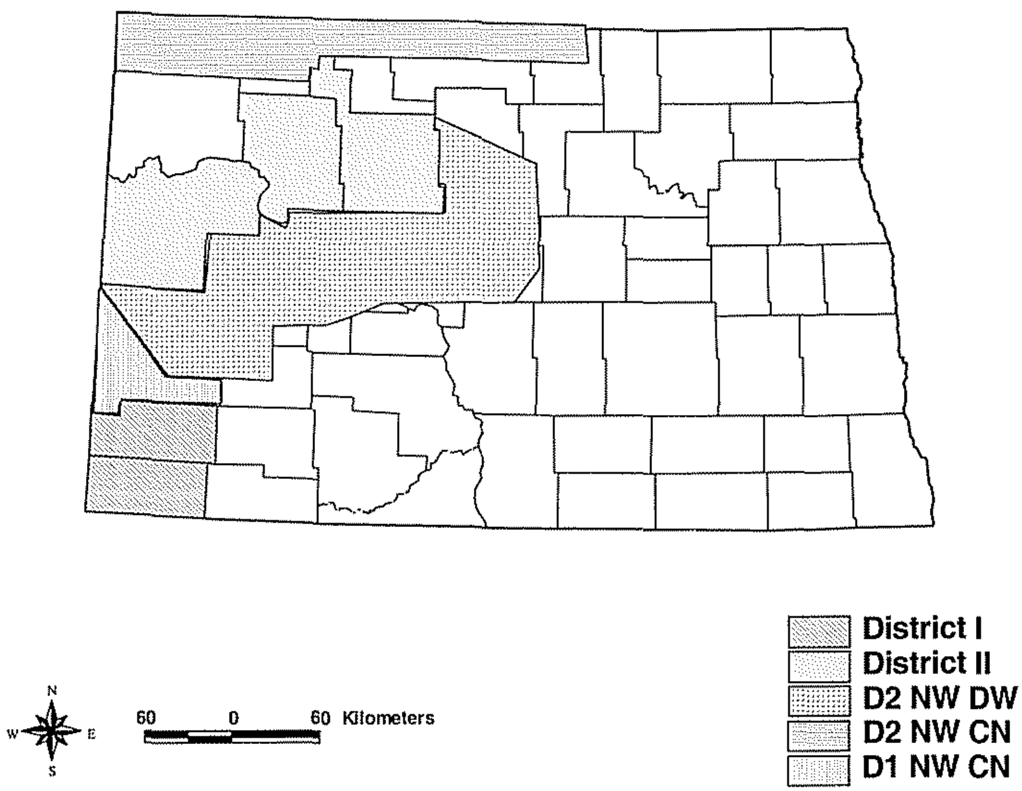


Figure 11. Northwest flow target, downwind, and control regions for both Districts I and II.

The downwind regions were subjectively defined based on the 1999 to 2002 storm flow data for both districts and flow regimes. This was done by defining the downwind regions that were thought to have been affected by seeding. Some of the downwind region did not start at the corner of the target regions, because a very small area would have to be seeded for these portions to be downwind of seeding activities.

As mentioned in Chapter 1, there were counties that participated in the NDCMP for a portion of the period. These counties were located in the downwind regions. Rainfall data was excluded from these counties for the years they were active in the project because seeding activities in a downwind region could bias the results. None of these counties were included in any portion of the control regions.

Wind Flow

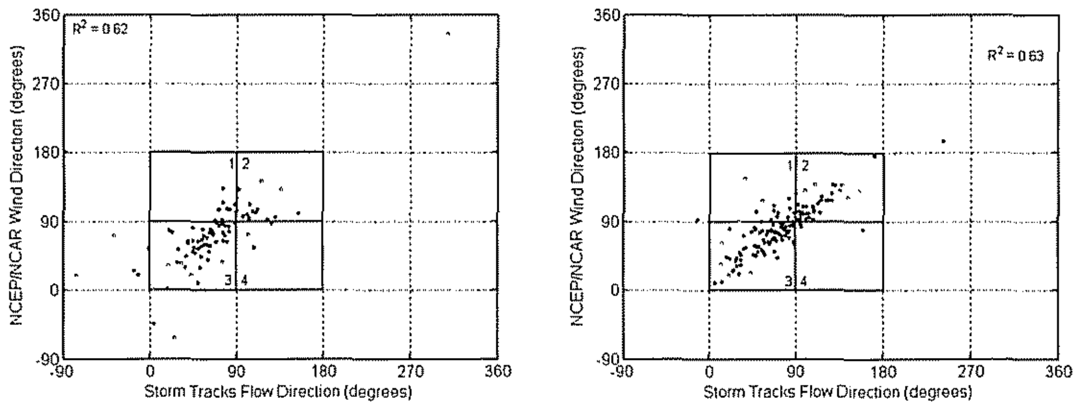
On days seeded, there were suitable clouds in the target regions that produced rainfall. Just using days seeded in the evaluations could have incorrectly shown increased rainfall in the target and downwind regions, when in fact, there may not have been. On a given day, one area could receive rainfall when areas relatively close by may not. Over an extended period, this problem should not exist. However, by using days seeded, the rainfall difference between the target/downwind regions and the control regions may be inflated in favor of the target/downwind regions. To account for this, every day was used when the wind was out of the northwest or southwest. If the wind flow was determined to be from a direction other than a northwest or southwest flow, or if it was from due west (90°), that day was not used.

The wind flow for every day in the summer months of 1977 to 2003 was determined in the following manner. Comparisons of the NCEP/NCAR 700, 600, and 500 mb pressure level data were made with the storm tracks data. The wind data from NCEP/NCAR were available at four different times during the day. For each pressure level and each time period, combinations of the times were used to determine which one best compared to the storm track data. The combinations of the times were determined by calculating a mean u and v wind component for all combinations. The combinations of times were calculated using the 12, 18, and 0 UTC the next day for the 700, 600, and 500 mb pressure levels. For each pressure level, the 12 UTC winds were compared to the storm tracks along with the 18 UTC, the 0 UTC, the mean 12 and 18 UTC, the mean 12, 18, and 0 UTC, and the mean 18 and 0 UTC winds. The pressure level and time that best represented the storm flow according to the storm tracks data was used. An R^2 value, (the coefficient of determination in regression or analysis of variance), was calculated for every comparison to determine how well the pressure level and time combinations represented the same flow regime as the storm tracks data. For example, if the storm tracks indicated the flow was from the northwest, the pressure level that compared best with the TITAN storm tracks was used as the representative level.

For District I, the Reanalysis wind data from the constant pressure level of 600 mb at 18 UTC provided the best comparison with the storm tracks data with an R^2 value of 0.62. A perfect correlation would have an R^2 value of 1.0 and if no correlation were present, the value would be 0. The R^2 value for this case indicated reasonable correlation. For District II the pressure level of 600 mb and a mean wind direction for the synoptic times of 12, 18, and 0 UTC the next day were found to have the best comparison, with an R^2 value of 0.63. There were not large difference between the different time combinations, but still the one that best represented the storm flow was used.

Figure 12 shows the comparison between the storm tracks and the NCEP/NCAR wind data for both Districts I and II. In these plots, the abscissa indicates the estimated storm tracks direction for seeded days from 1999 to 2002, and the ordinate corresponds to the NCEP/NCAR wind directions for the same days. If the storm tracks data or the

NCEP/NCAR wind data were in the first quadrant (wind direction of 0° – 90°) and the other was in the fourth quadrant (270° – 360°), the one in the fourth quadrant was made negative to account for the discontinuity between angles 0° and 360°.



(a) (b)

Figure 12. Comparisons of the storm tracks data with the NCEP/NCAR wind data for a) District I and b) District II.

In Fig. 12, it is seen that the comparisons for Districts I and II were similar. Generally when the tracks storm flow angle increased (0° – 360°), so did the reanalysis wind direction angle. There were a number of cases when the storm tracks and NCEP/NCAR wind data did not agree with the flow regime, and these cases fell outside of boxes 2 and 3 shown in Fig. 12. The wind and storm flow vectors in box 1 occurred when the NCEP/NCAR wind analysis indicated flow from the northwest and the storm tracks data showed flow from the southwest. Vectors in box 4 were created when the storm tracks had the flow from the northwest and the NCEP/NCAR wind data had the flow from the southwest. If either the NCEP/NCAR wind field or storm tracks data have the flow from the east, the vectors are not located within the boxes in Fig. 12.

The storm tracks data were treated as truth in this study and a relative error was calculated to determine how often the storm tracks and NCEP/NCAR wind data were not in agreement with the estimated flow regime. These errors were 16.5% for District I and 13% for District II. These errors were calculated by counting the number of times the storm tracks flow and the NCEP/NCAR wind fields did not agree on the same wind flow regime, (i.e. storm tracks flow was from the southwest, NCEP/NCAR wind flow from the northwest). Then, the number of times the two data sets did not agree was divided by the total number of days the storm tracks and NCEP/NCAR wind data was compared. This value was the percentage of times the two data sets did not define the same flow regime.

By considering only the error when either the NCEP/NCAR wind data or storm tracks data had a northwest flow and the other had a southwest flow, the error for District I became 14% and 11% for District II. There were only a few days seeded when the flow was from the east and only a small error when either the NCEP/NCAR reanalysis wind data or the storm track data had the flow from east and the other had it from the west. Therefore, the effects of the error in these cases should have been minimal with respect to the small number of cases that were seeded when the flow was from the east.

The majority of the errors between the storm tracks data and the NCEP/NCAR wind fields occurred when the storm tracks had the flow from the southwest and the NCEP/NCAR wind data indicated a northwest flow (box 1). Most of the vectors in box 1 are in the lower right hand corner of the box. This indicates that both the storm track and the NCEP/NCAR wind data indicated westerly flow, where the storm tracks data estimated a slight southwest movement and the NCEP/NCAR wind data indicated a slight northwest movement.

The differences between the NCEP/NCAR Reanalysis wind data and storm tracks data could have been caused by several factors. One factor could have been errors in the storm tracks estimated by TITAN, as discussed in Chapter 2. A second factor could have been the location of the NCEP/NCAR data grid point. The NCEP/NCAR data were taken from the grid point closest to the center of each district, and there could have been occasions when the wind was slightly different from the cell locations. A third factor could have been a difference between the times of the storm tracks and the NCEP/NCAR data. The wind could have changed direction between the time of the storms and the time of the reanalysis data.

It is also possible that storm movement could have been different than the upper level wind flow. Convective storms can propagate or move in a direction different than that of the upper level wind flow, so this might have been a contributing factor in the error between the storm tracks and NCEP/NCAR wind data. Most supercell storms propagate to the right of the actual mean flow; these storms are called right movers. Supercell storms are large rotating thunderstorms whose updrafts and downdrafts are organized in a way that it is able to maintain itself for hours. In supercell storms the new updrafts generally form on the right side of the storm, therefore, causing the storm to move to the right of the upper level wind flow. Supercell thunderstorms can form over western North Dakota. By observing the NDCMP 1999 to 2002 radar data, there were stronger storms that moved generally in a direction to the right of the rest of the storms. In most of the observed cases, the general flow of the storms was a southwesterly flow with the stronger storms tending to have a more west southwesterly movement.

Multicell thunderstorms also develop over this region. In multicell thunderstorms the individual cells move with the upper level winds, but the entire storm moves to the right of the upper level wind because new cell development. When a cell weakens, a new cell develops to the right of the old cell, which moves the storm to the right of the wind flow. TITAN tracks the movement of cells, not storms, so the storm tracks would have been the same as the mean storm flow on these days. However, in multicell storms, cells weaken and new cells develop, and it was possible that a cell weakened below the threshold of 30 dBZ and the new cell developed and strengthened over the threshold from one scan to the next. This would show the cells moving to the right of the upper level flow. If the tracks correctly tracked the cells, then the storm tracks would have been the same as the wind flow.

The differences between the storm tracks data and the NCEP/NCAR wind data might have been small, but they could have had different flow regimes. For example, the storm tracks data could have a wind from 92° and the NCEP/NCAR wind data had a direction of 88°. These two directions are very close, but they would have selected different flow regimes. It was determined that, on average, more rain fell on days when the wind was from the southwest than the northwest, which could have been important if the wind regime was incorrectly assigned. It was also discovered that, on average, there were more days when the flow was from the northwest than the southwest. This indicates that precipitation on southwest days was heavier and more intense than the precipitation that fell on northwest flow days. For example, suppose the reanalysis data indicated a northwest (drier) flow regime when the flow was actually from the southwest (wetter). If the effect of seeding were to increase rainfall, this error could have increased the differences between the target/downwind regions and the control regions for the northwest regions, and decreased the effect for the southwest regions. Given the error calculated between the NCEP/NCAR reanalysis and storm tracks data, this error was observed.

Rainfall Evaluation

The precipitation amounts for each region (target, control, downwind) were calculated for the full study period (1977-2003 for District II for southwest and northwest flows, 1977-1998 for District I with a southwest flow, and 1978-1998 for District I with a northwest flow). All gauge data in the target, downwind, and control regions were combined to obtain a mean daily rainfall amount for each region for each wind regime and district. At the end of the month, all the daily means were added to get a monthly rainfall amount for each region. A seasonal rainfall total was calculated by adding all the daily rainfall amounts, in each region, for the entire season. These values were used to calculate a mean for each month and the season total.

The daily rainfall amounts for each region were calculated by the following:

$$R = \frac{\sum_{i=1}^{n} r_g(i)}{n} \tag{1}$$

where R is the calculated mean daily rainfall amount for the given region, n stands for the number of gauges that were operational in the region that day, and r_g represents the rainfall amount recorded on the given day by the rain gauge. Next, a monthly rainfall amount ($R_{Df\_monthly}$) was calculated for each region and wind regime:

$$R_{Df\_monthly} = \sum_{i=1}^{n} R(i) \tag{2}$$

where R was the daily mean rainfall amounts for the given region and n is the number of days for the given month that the wind was from that region's wind regime. Then, a season total rainfall amount was calculated for each region for the entire season in the same manner as equation 2. Finally, the monthly and seasonal mean rainfall amounts for each region were calculated for the entire period of the study for each district and flow regime.

A comparison between the target and control and the downwind and control was conducted. Using the monthly means and the summer total, a ratio test was applied to the different regions to see how much more or less rainfall the target and downwind regions received than the control regions.

Climate Rainfall Data

Because of the non-uniformity of rainfall across North Dakota, the difference between the target and downwind regions and the control regions calculated above could have been due to the natural variations in rainfall. To account for these variations, a climate adjustment was applied to the data. Climatological summertime rainfall data from 1931 to 1960 (prior to seeding activities) were used to determine the natural variations in rainfall throughout the state.

A climate mean rainfall amount for all the regions was calculated using the North Dakota climate records for June, July, and August. Also, gauges located in Montana and South Dakota were used. A Cartesian grid was applied across the state with a 25 km grid spacing. The Cartesian grid and the climate rain gauge locations are given in Fig. 13. The 25 km grid spacing was chosen because of the climate gauge locations.

It can be seen that there was a lack of climate gauges in the north and northwestern portion of North Dakota and there are no climate gauges located north of the state. This could have led to boundary problems when calculating the climate ratio for the regions in this area. Those few climate gauges may not have correctly represented the whole region, producing an under or overestimate of climate rainfall amount. Unfortunately, without any other climate gauges, the size of this possible error could not be calculated. There was one region that was fully located in this data-sparse area, the control region for District II with a northwest flow.

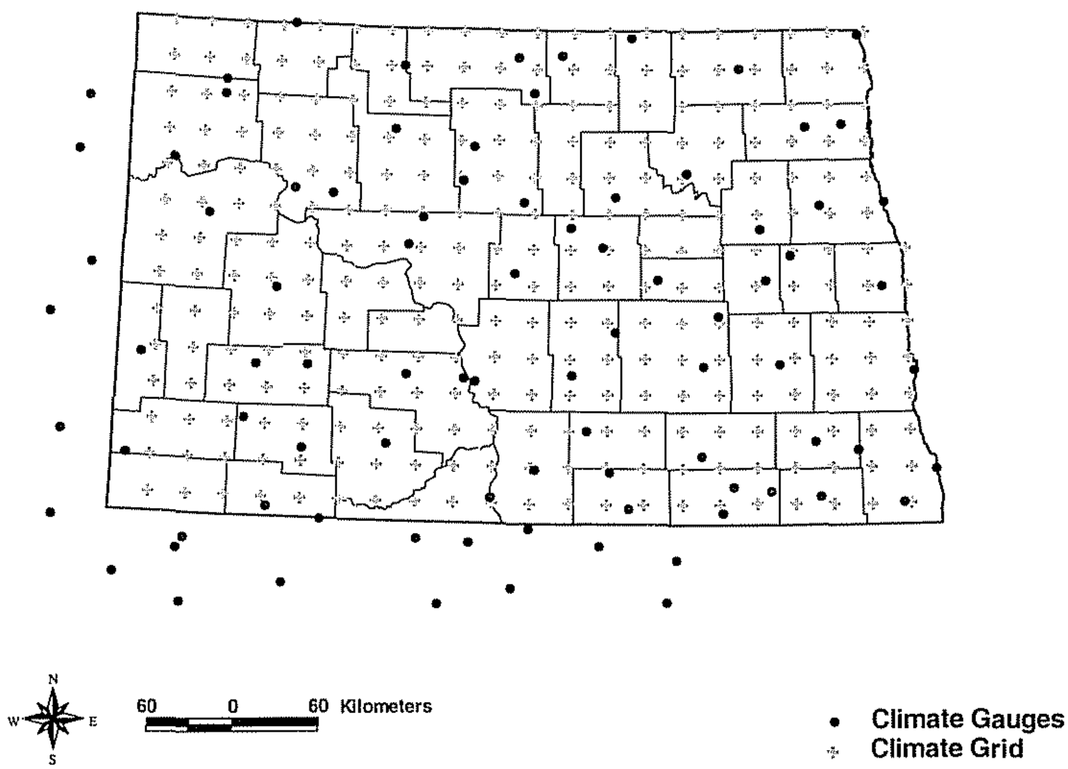


Figure 13. The 1931 to 1960 climate rain gauge locations and a 25 km grid across North Dakota.

Each climatological rain gauge that was within 100 km radius of a grid point was weighted to each grid point, using a Cressman distance-weighting scheme given by:

$$w = \frac{R^2 - d^2}{R^2 + d^2} \tag{3}$$

where w is the weight function, R is the radius of influence, and d is the distance of the gauge from the grid point. After the weight was calculated, the rainfall amount at the grid point was calculated by:

$$f_a = \sum_{i=1}^{n} w(i) * f_o(i) \tag{4}$$

where f_a is the calculated rainfall amount at the grid point, f_o is the observed rainfall amount of the rain gauge, w is the weight calculated in equation 3, and n is the number of gauges that fell within the radius of influence of the given grid point.

Once the gauges were weighted to the grid points, a mean climate rainfall amount was calculated for each region using all the grid points that were in that region. Then, a rainfall ratio was calculated between the target/downwind regions and their corresponding control regions. The ratio between the target and control regions (TC) was calculated for the given district and flow regime by the following:

$$TC = \frac{T}{C} \tag{5}$$

T stands for the climate rainfall amount for the target region, and the C represents the climate rainfall amount for the control.

The climate ratios between the downwind and control regions (DC) were calculated for the given District and flow regime by the following:

$$DC = \frac{D}{C} \tag{6}$$

where D stands for the climate rainfall amount for the downwind region. The ratios were computed for each month and for the season.

Next, the ratios were applied to the control regions for all three months and the summer total for both districts and flow regimes. They were applied by multiplying a given control region rainfall by its climate ratio. *TC* was applied for the comparison between the target and control regions and *DC* was applied for the comparison between the downwind and control regions. The climate adjusted rainfall was used to evaluate the effects of summertime seeding.

Monte Carlo Test

A Monte Carlo test was applied to the climate adjusted rainfall data to infer the statistical significance of the seasonal difference of rainfall between the target/downwind regions and the control regions. The objective of Monte Carlo simulation is to construct or evaluate a distribution that is difficult or impossible to construct analytically. It is a way to generate many solutions or sets of solutions in accordance with a specified probability distribution. For this test, the null hypothesis was that seeding does not affect rainfall amounts in the study areas. The test methods were partly based on those used in a study conducted by Dennis et al. (1975).

The Monte Carlo test provides a measure to determine if the differences in rainfall amounts between the target/downwind regions and the control regions could have occurred naturally, and therefore, not been significant. For example: if the difference showed that the target and downwind regions received more rainfall than their corresponding control regions, the increase in rainfall does not necessarily mean seeding was the cause. The NDARBCON was a dense network of gauges; in many locations, there were gauges grouped fairly close to each other. On average the gauges were located 5 to 15 km apart of each other. It was common to have a group of gauges, (usually 3 to 5 gauges), located within 15 km of each other. If a close group of gauges were in the target region and there was only one gauge in the control region when a storm producing heavy rain moved over each gauge grouping, the target region would have more weight from this one storm compared to the control region. If both regions received the same amount of rain, but since there were more gauges affected by the storm in the target region, it would appear that the target region recorded more rainfall.

To make the test uniform and systematic for all years of data, the rain gauges available in a given year were transformed to a Cartesian grid. To account for the problem of a non-uniform rain gauge network and changing gauge locations, a grid was created throughout western ND with a 15 km horizontal grid spacing. The horizontal grid spacing of 15 km was chosen because of the variability of summertime precipitation and the distribution of the ND ARBCON gauge locations. Due to the variability of summertime precipitation, a small grid point spacing was needed. The distribution of the rain gauges for the 27-year period was examined to determine the grid point spacing that would best represent the data, and a grid point spacing of 15 km was used. The grid was set up to represent all portions of a region, but not over-represent areas of maximum rainfall events in a region. Since summertime precipitation is variable over short distances (i.e. several kilometers), smaller grid spacing was needed. For each grid point, the rain gauge data were weighted to the corresponding grid cells for gauges within 20 km of that particular grid point. There were years when some grid points did not have any gauges within 20 km and these grid points were not used in this study. In 1977 and 1978, there were regions with only a few usable grid points, so these two years were excluded from the Monte Carlo test. The year 1979 was excluded from the Monte Carol test for District I to allow grid points in Adams County to be included.

The target, downwind, and control regions varied in both size and number of gauges with respect to each other. The number of grid points used were determined by the number of grid points available in the control region because they were smaller than the target/downwind regions. The same number of grid points were selected from the target/downwind regions, using points that best represented all areas of the region. This was done by manually viewing the gauge locations for every year and month with respect to the grid points to determine which grid points had at least one gauge within 20 km for every year and month. Grid points from all portions of each region were selected. This provided the target/downwind regions and their corresponding control regions with same number of grid points. Grid points in the downwind regions that had seeding activities take place were excluded from the Monte Carlo test.

When selecting the grid points, it was discovered that it was common to have groups of rain gauges in one area and no gauges over other portions of a region. In some years there was a large concentration of gauges in one portion of a region, and in other years, a large concentration of gauges were located in different portions of the region. The grid points were selected in a manner that represented every portion of a region when possible and not just areas of high gauge concentrations. However, because of the change in gauge locations, not all portions of regions could be represented.

Since the hypothesis of the Monte Carlo test was that seeding does not affect rainfall amounts which would infer the location of a rain gauge should not matter, any rain gauge within 20 km of a grid point was weighted to that grid point even if the gauge and grid point were in different regions. When a grid point was close to a border of a region, it was possible that a rain gauge in the adjacent region would be more representative. This only occurred when a grid point was close to a border of a region and there were only a few grid points weighted with gauges from a different region. When a grid point was close to the boarder of a region and a rain gauge in an adjacent region was weighted to it, that gauge was not used for a grid point in the adjacent region. If the same gauges were weighted to grid points in both the target/downwind and the control region, this could bias the results.

The Monte Carlo test was used to estimate the significance of the difference in rainfall amounts between the target/downwind regions and the control regions. Since the hypothesis was that seeding had no effect on rainfall amounts in the region, the grid points from the target/downwind region and the corresponding control region were randomly interchanged. For each Monte Carlo simulation, there were n (16 for District I and 22 for District II) number of grid points between the target/downwind region and the corresponding control region. Half of the grid points were located in the target/downwind and the other half was located in the corresponding control region. The grid points were numbered 1, 2, 3, …,n with each number representing either a target/downwind grid point or a control grid point, where the first $n/2$ grid points were considered in the downwind/target region, and the set of grid points were considered in the control. The grid points were then randomly sorted, so the order was no longer ascending. Then, the first $n/2$ number of grid points was categorized as target/downwind and the last $n/2$ number of randomly sorted grid points was categorized as control. If seeding had no effect on rainfall amounts, interchanging grid points between the target/downwind region and the control region should not change the difference between the regions.

The significance cannot be determined by just interchanging the grid points between the regions once. This needs to be repeated many times to determine if the original difference occurred again or surpassed a large number times in order to determine if the original difference was significant or not. It was decided that the statistical test would be repeated 1000 times. This was because it was thought that by repeating the test 1000 times would have been a large enough sample to be able to determine the significance of the rainfall differences.

The mean seasonal difference between the target/downwind region and control region was calculated. Only the seasonal mean was calculated because breaking the data into subgroups would create the potential to have too many categories, which would cause multiplicity issues in the statistical analysis. For example, it was possible that more rain fell in the target region in June naturally and was not affected by seeding. By breaking the data in to subgroups, (i.e. June, July, and August), a false significance could have been calculated just by random selection. Therefore, the data were examined on a seasonal basis to reduce the issue of multiplicity.

In the Monte Carlo test, the grid points were randomly sorted and interchanged between the target/downwind region and its corresponding control region. A mean seasonal rainfall amount was calculated for the regions, and then a difference between the regions was calculated for 1000 iterations. The difference between each target/downwind and control region was compared to the original difference between the two regions. The number of times the original difference was recreated or surpassed was used to estimate a *p-value*. The *p-value* is the specific probability or frequency that the observed value of the test statistically will exceed a selected probability for a given sample. Any *p-value* greater than 10% was considered to support the hypothesis, therefore, any *p-value* 10% or less was considered significant, and the hypothesis was rejected. The methodology of the Monte Carlo test mentioned above, can be seen in the flow chart shown in Fig. 14.

It was stated earlier that an incorrect significance could have been computed by breaking the data into subgroups. In this test, the data was categorized into southwest flow days and northwest flow days. Therefore, it was possible that an incorrect significance could have been found because the rainfall data were categorized into these subgroups because of multiplicity reasons. It has been mentioned that because of the rain gauge network used, days had to have been divided into southwest days and northwest days. The effects that could have been present by dividing the days into southwest days and northwest days were unknown. This error was likely to have been less on southwest flow days, due to the larger sample size for southwest flow days. This test provide inferences if seeding could have caused a statistically significant increase in rainfall in the target/downwind regions.

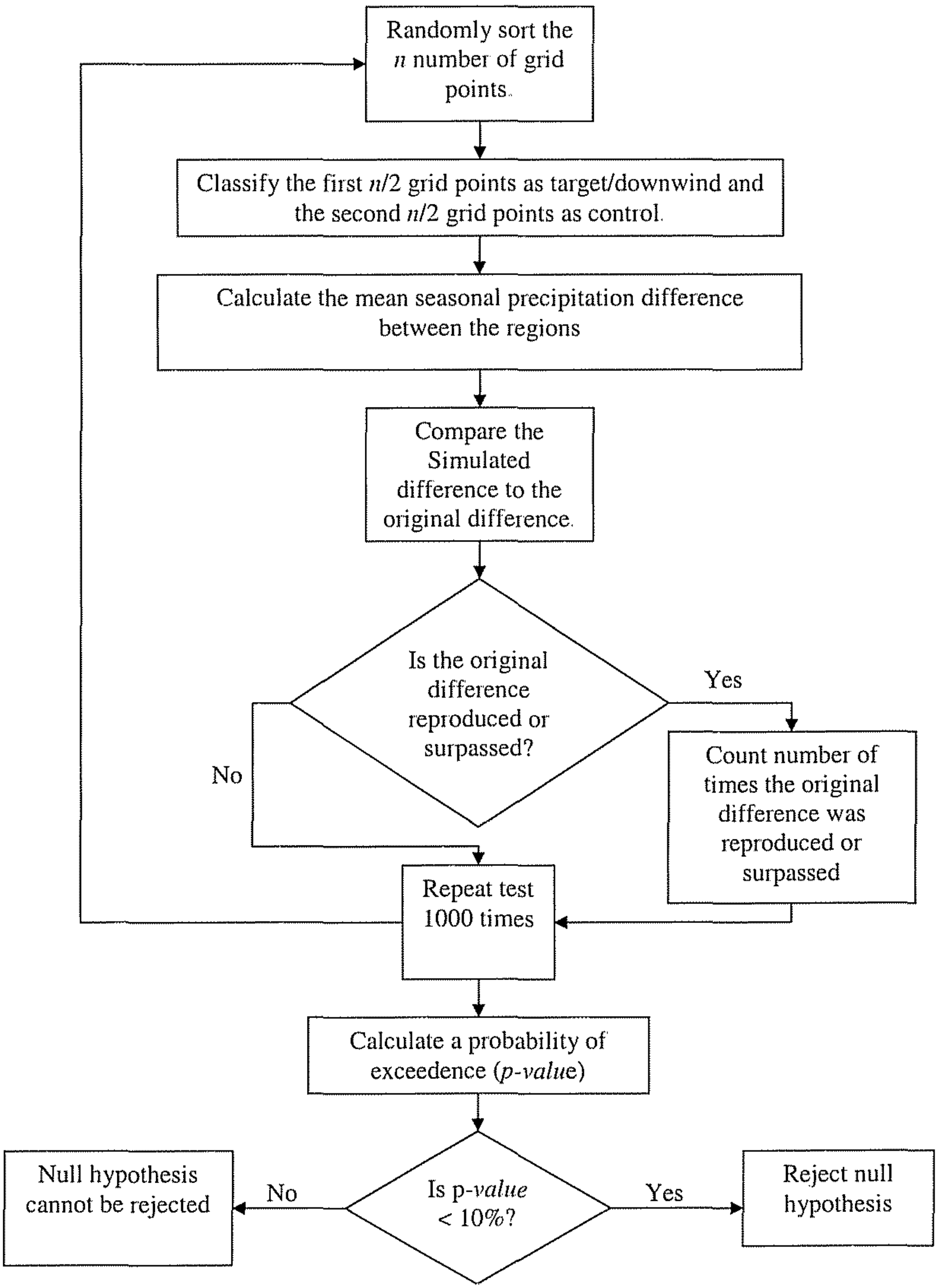


Figure 14. Flow Chart of the Methodology of the Monte Carlo test conducted in this study.

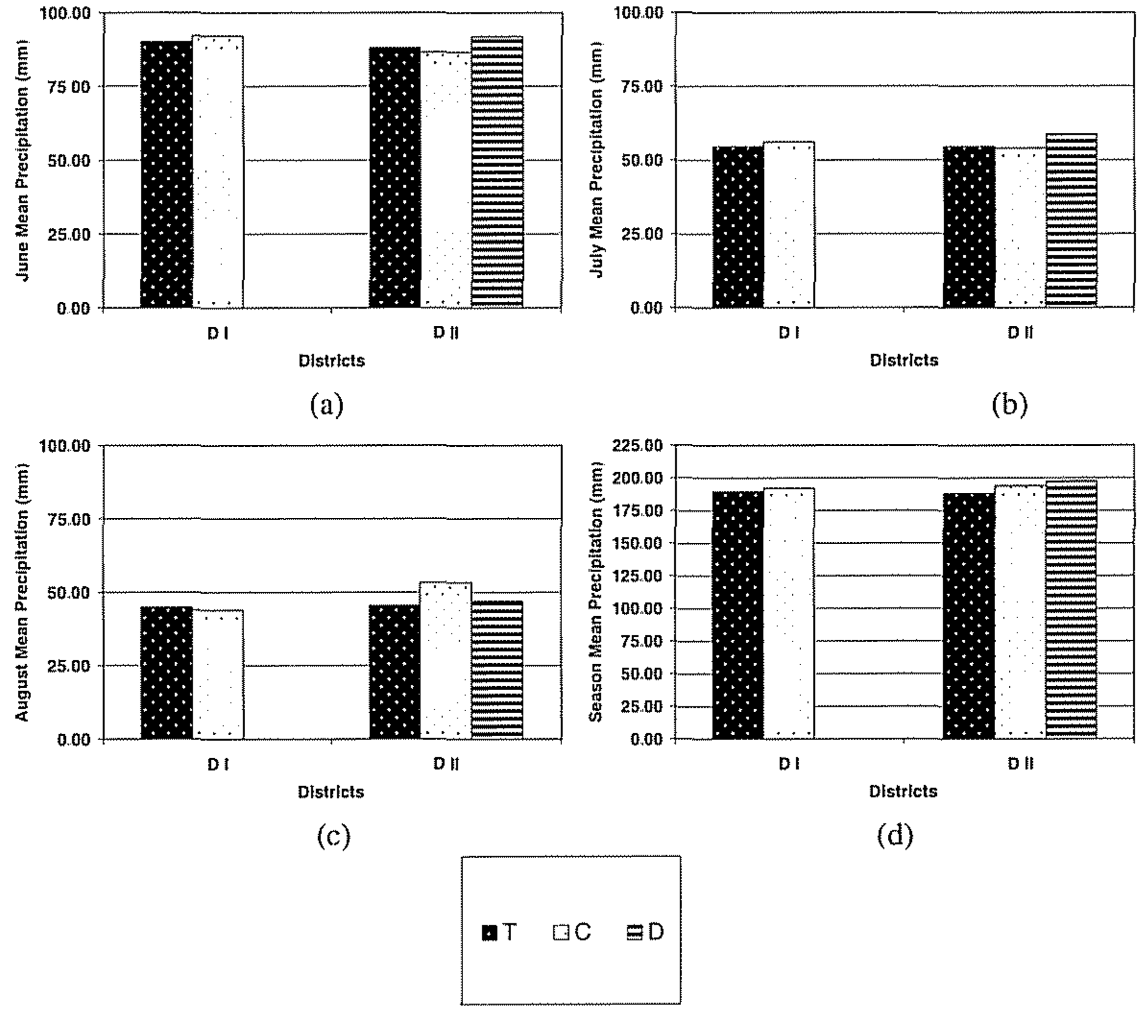
CHAPTER 4

RESULTS

Climate Data

The climate rainfall amounts for Districts I and II for June, July, August and the summer can be seen in Fig. 15. *T* stands for the target region, *C* for the control region, and the *D* for the downwind region. For a northwest flow for District I, the climate data indicated that the control region received 2%, 3%, and 1% more rainfall than the target region for June, July, and the season total respectively, and 2% less for August. For District II with a northwest flow, the climate data indicated that the control region received 15% and 3% more rainfall than the target in August and for the seasonal total respectively, and the target received 2% and 1% more rainfall in June and July, respectively. The control region received 12% more rainfall than the downwind region in August, and the downwind region received 6%, 9%, and 2% more rainfall in June, July, and the season total respectively, according to the climate data.

In District I and II with a northwest flow, the wettest month according to the climate data was June, when average rainfall was more than 25 mm greater than July and nearly 50 mm greater than August. Most seeding activities took place in June closely followed by July, and there were only a few days seeded in August on average.



Legend

Figure 15. Northwest flow regions 1931 to 1960 mean monthly rainfall amount in mm, a) June upper left, b) July upper right, c) August lower left, and d) seasonal mean lower right.

The climate rainfall amounts for a southwest flow for June, July, August, and the season can be seen in Fig. 16. For a southwest flow, the differences in climatological rainfall amounts for each district were very similar to each other. The only exception was August where the District II downwind region received 23% more rainfall than the control region. On average, there was also a peak in rainfall in June for a southwest flow.

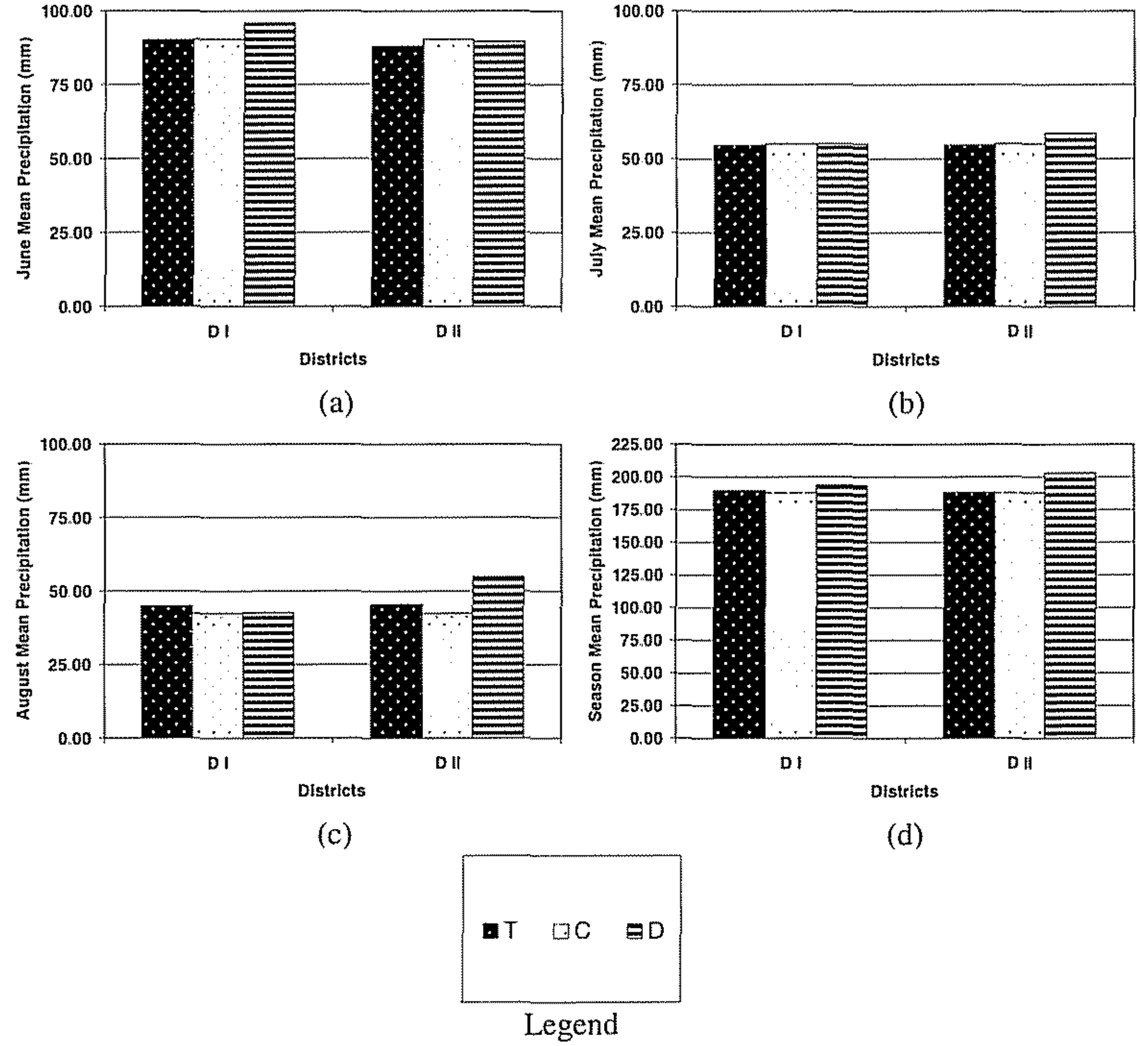
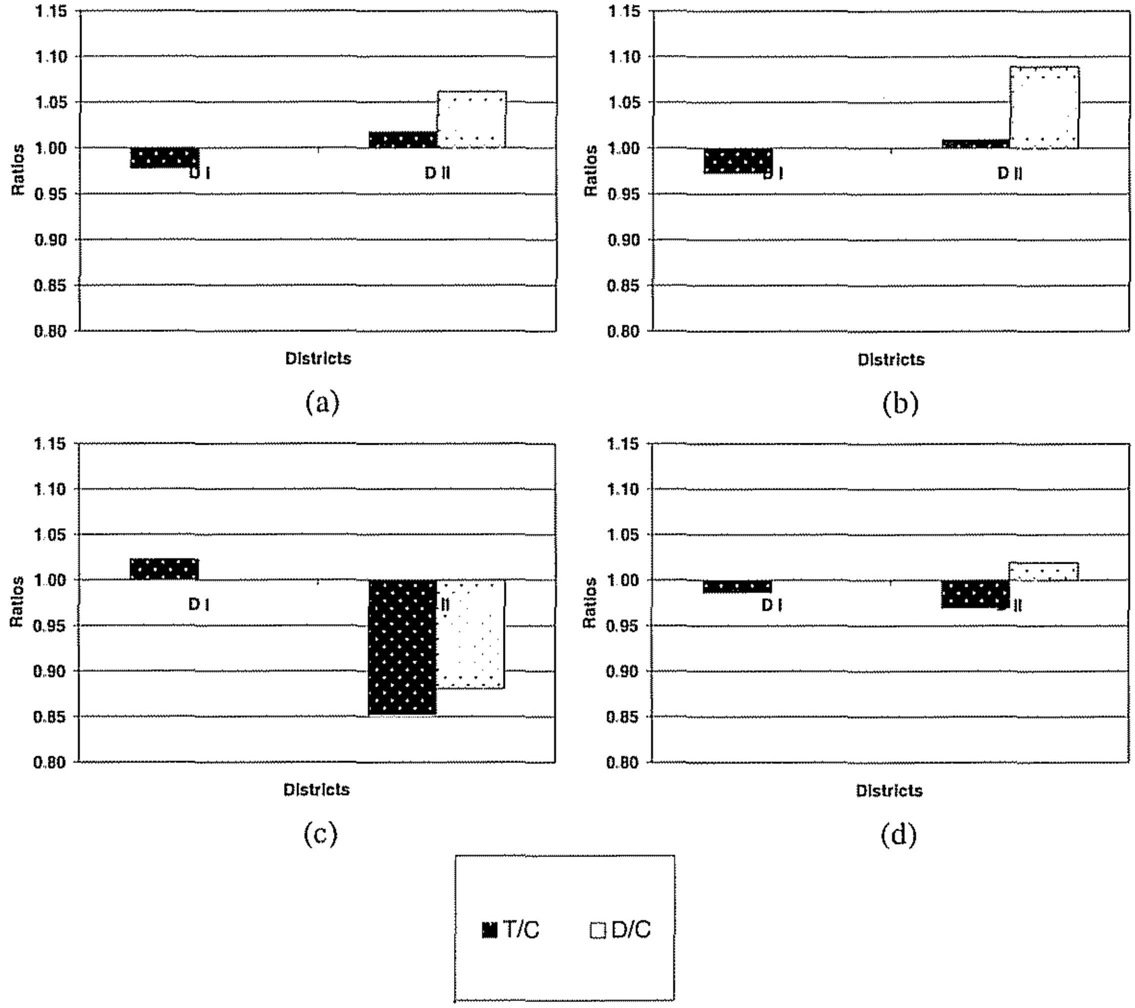


Figure 16. Southwest flow regions 1931 to 1960 mean monthly rainfall amount in mm, a) June upper left, b) July upper right, c) August lower left, and d) seasonal mean lower right.

Climate adjustment ratios were calculated between control-target and control-downwind for both districts and flow regimes. The ratios for a northwest flow regime for both districts are shown in Fig. 17 for June, July, August, and the season. The *T/C* stands for the ratio between the target and control regions, and the *D/C* stands for the ratio between the downwind and control regions.

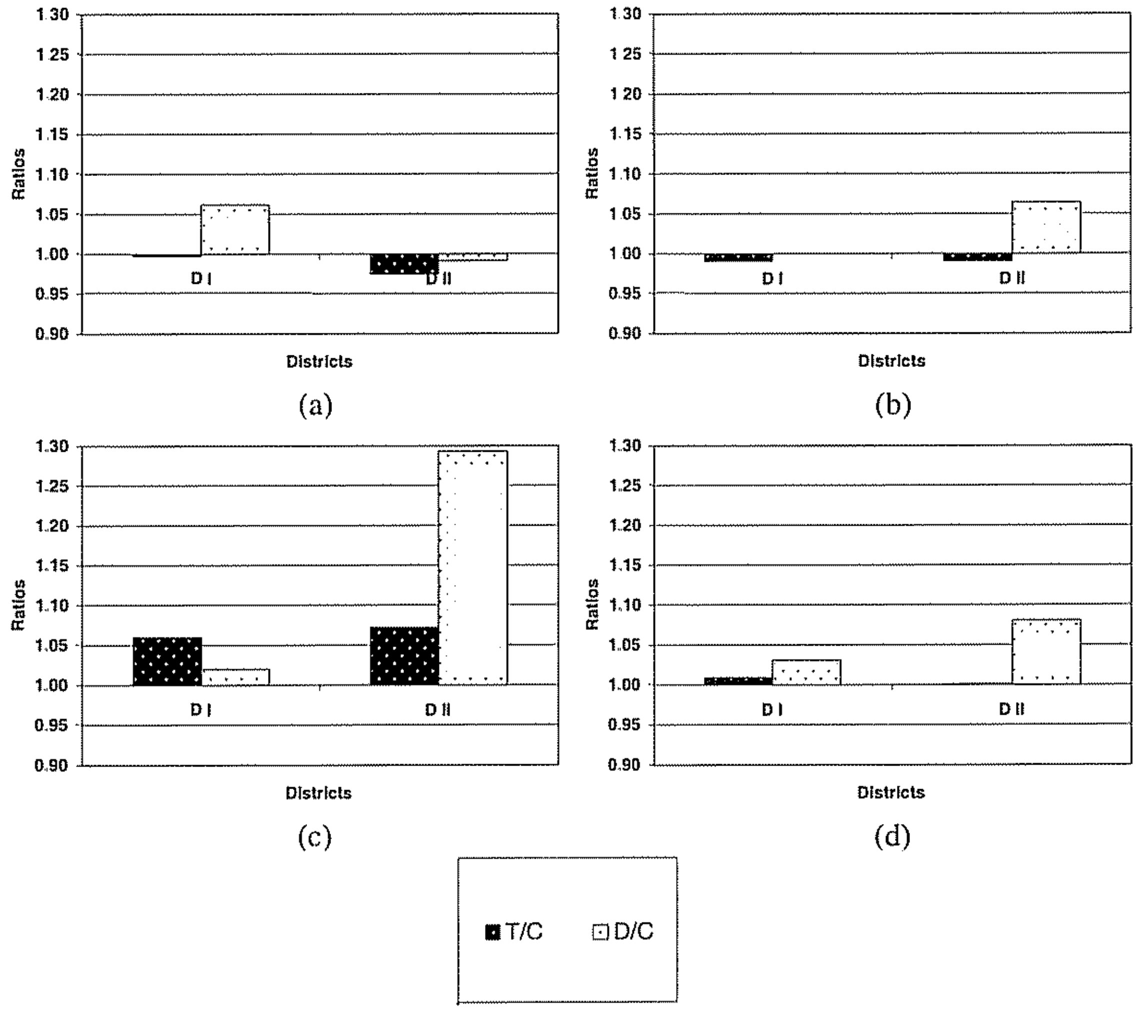


Legend

Figure 17. Northwest flow regions 1931 to 1960 ratios between the target/downwind regions and the control regions, a) June upper left, b) July upper right, c) August lower left, and d) summer ratio lower right.

For northwest flow, the control-target climate ratio for District I was negative for June and July, and positive for August. The seasonal ratio was negative based on the monthly statistics. This means that the control regions received more rainfall than target regions from 1931 to 1960 in June, July and overall for the season, but received less in August.

For District II the target and downwind regions, climatologically, received more rainfall than the control region in the months of June and July. For both the target and downwind regions, the control region received substantially more rainfall in August over the climatic period of 1931 to 1960. For the seasonal rainfall totals, the control region received more than the target and the downwind regions.



Legend

Figure 18. Southwest regions 1931 to 1960 ratios between the target/downwind regions and the control regions, a) June upper left, b) July upper right, c) August lower left, and d) summer ratio lower right.

The ratios for a southwest flow were also calculated in the same manner as the northwest ratios and can be seen in Fig. 18. The climate ratios calculated in this study showed that there were some large differences between the target and downwind regions and the control regions. The largest differences between the regions, on average, occurred in August. This is seen in the ratios, where the largest (smallest) ratios occurred. The terrain in North Dakota changes across the state, from Badlands in the southwest to flat plains in the east. The majority of the moisture for summertime precipitation in North Dakota comes from the Gulf of Mexico. The southeastern portion of the state is closer to this moisture; therefore, more rainfall occurs there.

Rainfall Analysis with Climate Adjustment

The rainfall amounts were calculated for each region using the ND ARBCON rain gauge data. Then, the climate ratios that were calculated by the climate rain gauge data for each region were multiplied to the control regions. Figure 19 shows the northwest flow adjusted rainfall amounts, where *T* is the target region rainfall amount, *CT* is the control region rainfall amount with target-control climate adjustment applied, *D* is the downwind region rainfall amount, and *CD* is the control region rainfall amount with downwind-control climate adjustment applied.

The target regions in District I received a larger amount of rainfall than the control for June, July and the season. However, the control received more rainfall in August. The largest difference between the target and control regions occurred in June and the smallest in July. For District II, the control region received a greater amount of rainfall than both the target and downwind regions for both June and July. The target and downwind regions both averaged more rainfall for August than the control region. For the season, the target region received slightly more rainfall than the control region, and the downwind region received less rainfall than the control region.

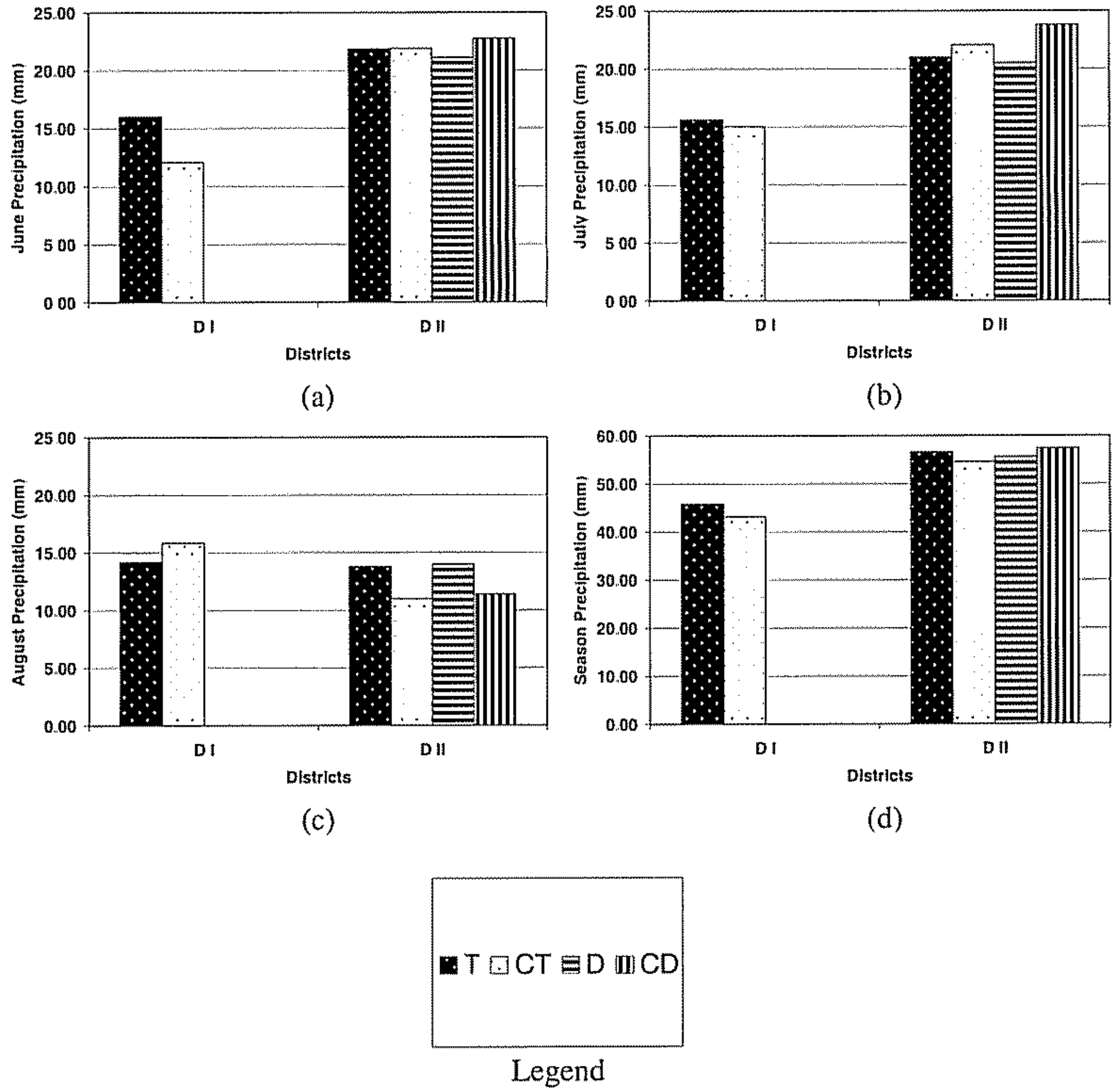
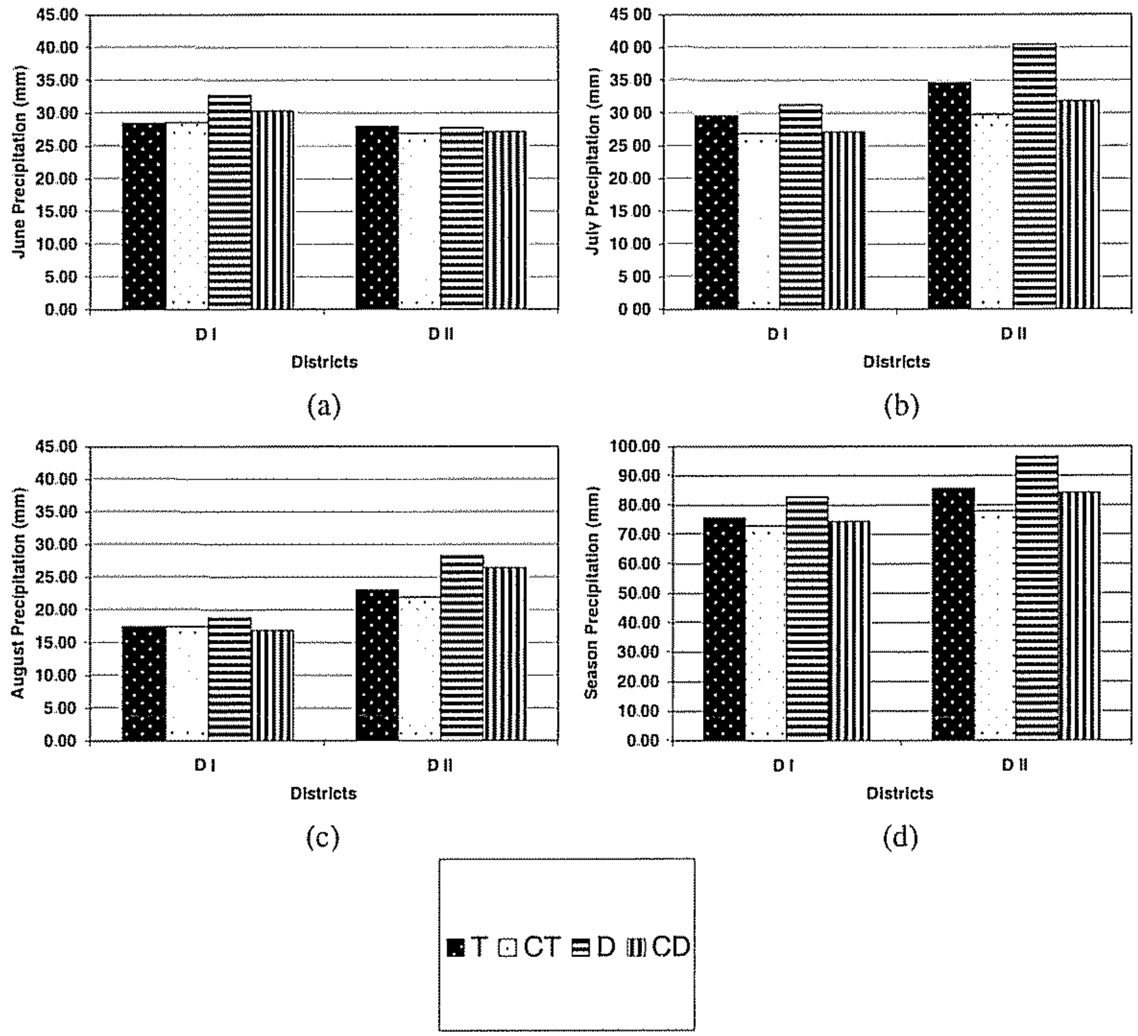


Figure 19. Northwest rainfall amounts with climate adjustment applied to the control regions, a) June upper left, b) July upper right, c) August lower left, and d) summer lower right.

The mean rainfall amounts for June, July, August and the season for a southwest flow for both districts can be seen in Fig. 20. For District II with a southwest flow, the target and downwind regions averaged about the same or more rainfall than the control region. The southwest regions for District II, recorded 4 to 14 mm more rainfall in July than in June in District II. For District I, the target region for the season averaged 2 mm more rainfall than the control regions. There was about the same amount of rainfall recorded in both June and July in District I.



Legend

Figure 20. Southwest rainfall amounts with climate adjustment applied to control regions, a) June upper left, b) July upper right, c) August lower left, and d) seasonal lower right.

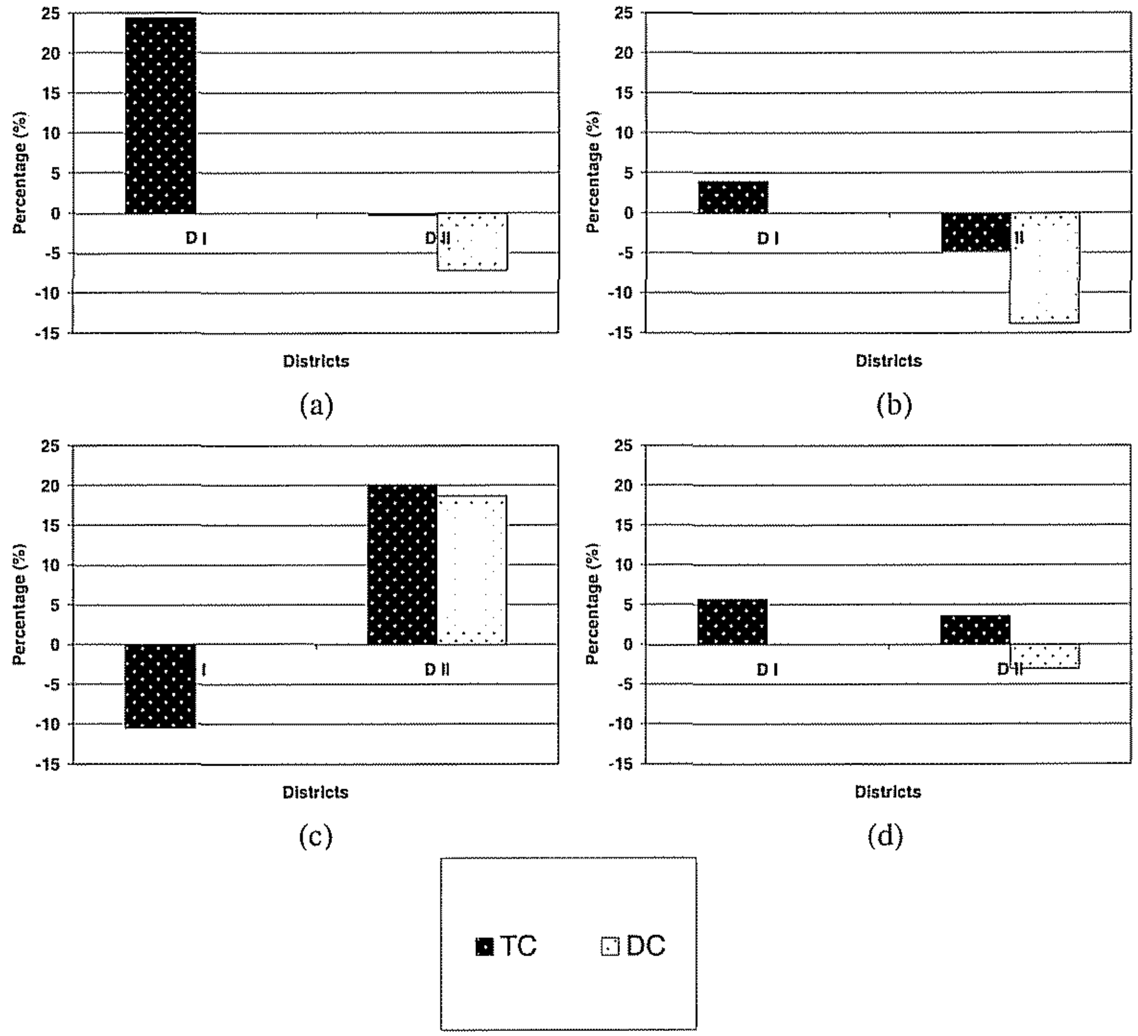
A percentage difference was calculated between adjusted rainfall amounts in the target regions and their corresponding control regions, and between the downwind regions and their corresponding control regions. The percentages were calculated between the target/downwind regions and the control regions for the 27-year, 21-year, and 20-year mean rainfall amount for the all three months and the season for the corresponding districts and flow regimes. The seasonal total mean rainfall amount was used to determine if the target and downwind regions received more rainfall than the control regions. Monthly values were examined to determine if there was a month where seeding effects were more pronounced. The percent differences for June, July, August, and the season total for a northwest flow can be seen in Fig. 21. In Fig. 21, *TC* is the percentage between the target and control regions, and *DC* is the percentage between the downwind and control regions.

A positive (negative) percentage exists when the target/downwind region averaged more (less) rainfall than the control region. The percentage difference in rainfall between the target/downwind and the control regions, seen in Fig. 21 & 22, were calculated by the following formula:

$$P_{tc} = \frac{T - C}{C} * 100\% \tag{7}$$

P_{tc} represents the percentage difference the target region received over the control region, C represents the control regions rainfall amount, and T represents the target regions rainfall amount. The downwind-control percentage difference was calculated in the same manner.

For District I with a northwest flow, the target region for June, July and the season averaged more rainfall than the control region. The seasonal percentage difference was 6% for the 21-year period. The biggest difference between the target and control region occurred in June with a percentage difference of 24%. In August, the control region averaged 10% more rainfall than that of the target region.



Legend

Figure 21. Northwest target/downwind regions difference with the control regions; with the climate adjustment applied, a) June upper left, b) July upper right, c) August lower left, and d) seasonal lower right.

For a northwest flow for District II, the target and downwind regions received less rainfall than the control region in June and July, and the downwind region received less for the season. Only in August did the downwind region receive more rainfall than the control regions. The target region had a greater amount of rainfall than the control in August and for the season. The District II downwind region with a northwest flow was the only target/downwind region that received less rainfall than the control region. The target region received about 3% more rainfall than the control region for the season and the control region received 3% more rainfall than the downwind region.

For District I with a northwest flow, the target region received more rainfall than the control in all three months and for the season. The smallest percentage difference occurred in August. The difference between the target and control region for the seasonal total was 6%. There were climate gauges in Montana, which would eliminate boundary problems in the climate ratio between the two regions. The control region used for District I with a northwest flow was north of the target region. If the wind flow was incorrectly determined to be a northwest flow when it should have been a southwest flow, it could have increased the target region and not benefited the control regions.

The percentage difference for the southwest region for both districts can be seen in Fig. 22 for June, July, August, and the seasonal total. For a southwest flow for District II, the target and downwind regions received more rainfall than the control region for both June and July, but both received less in August. The difference for July was > 10%. For the season total, both the target and downwind region received at least 5% more rainfall than the control region. The target received 8% more rainfall than the control region, and the downwind region received 13% more rainfall than the control region.

There was less rainfall recorded in the regions in August than in June and July. For the southwest flow cases, the amount of rainfall recorded in the month of August for all the regions was around 15 to 20 mm less than that recorded in June and July. For the northwest flow regime, the regions recorded around 10 mm less rainfall in August then did in June and July. On Average, for both wind regimes, the regions received about

40% more rainfall in June and July than in August. There were 30 to 35% more days seeded in June and July than in August.

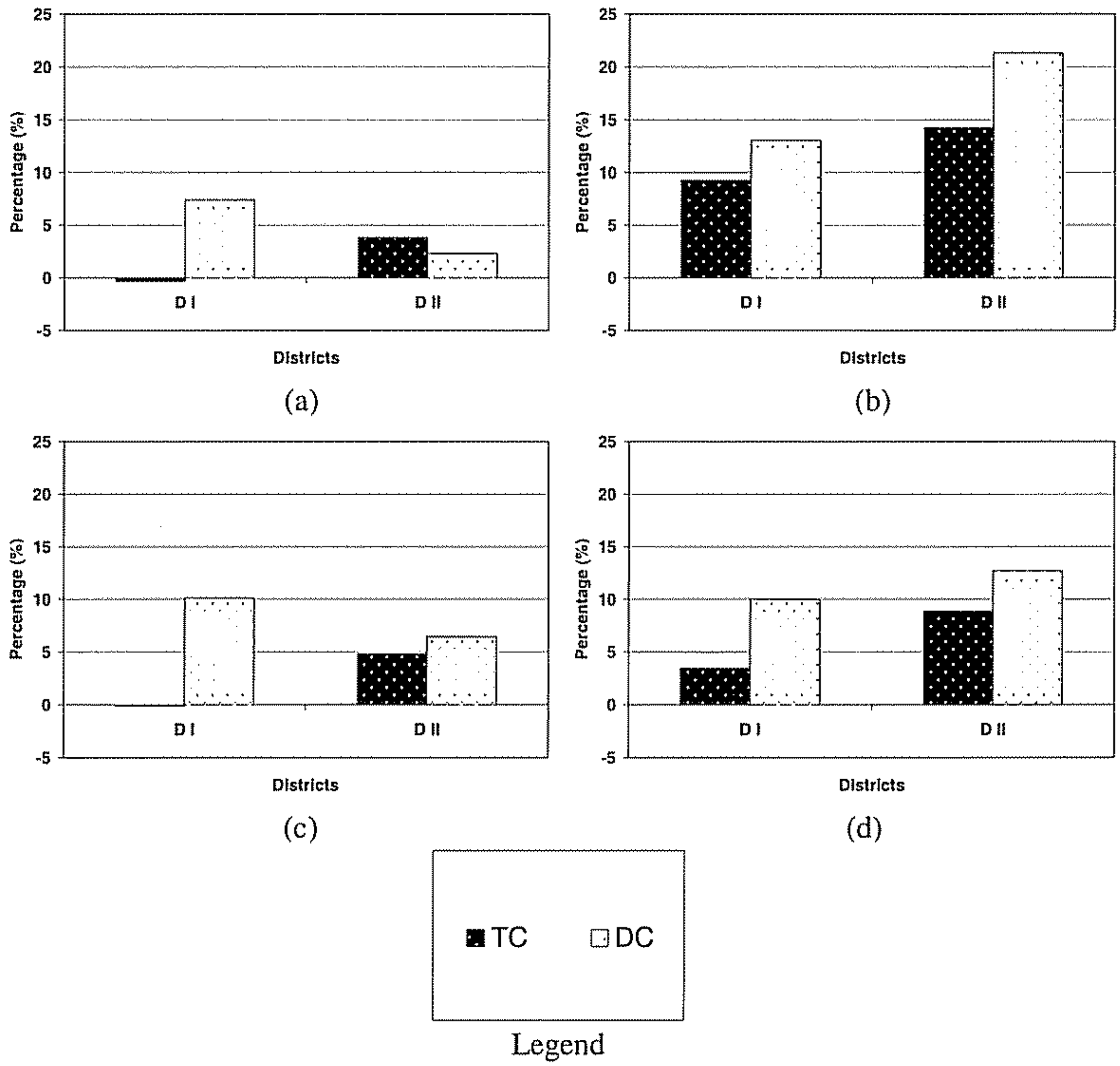


Figure 22. Southwest target/downwind regions difference with the control regions with the climate ratios applied to control regions, a) June upper left, b) July upper right, c) August lower left, and d) summer lower right.

For a southwest flow for the seasonal total for both districts, all the cases had the target and downwind regions receiving more rainfall than the control region. The downwind region for District I with a southwest flow received 10% more rainfall than the control region for the total season rainfall amount. An increase of 5% or more in the target/downwind region over the control region was considered significant because pervious studies showed a 5% to 10% increase due to seeding. The target and downwind regions for District II with a southwest flow received more rainfall than the control region for the season rainfall amount.

Monte Carlo Test Results

The results of the Monte Carlo test are discussed in this section. It was predefined that a p-value of 10% or less was considered significant. The *p-value* and original difference for the target/downwind regions and their corresponding control regions for both districts and flow regimes can be seen in Table 2.

In the Regions column, *TCN* represents the difference between the target and control region, and *DCN* represents the difference between the downwind and control region. The *p-value* column shows the summary of the fraction of times the differences calculated in the Monte Carlo test reached or surpassed the original difference. The *Original Dif* column provides a summary of the mean seasonal difference calculated between the target/downwind regions and the control regions, using the gridded data with the grid points in their true regions. A positive original difference means the target/downwind region received more rainfall than the control, and a negative difference means the control received more.

Table 2. Results of the Monte Carlo significance test of the difference between the target/downwind regions and the control regions for both Districts and flow regime.

District	Regions	Flow	p-value (%)	Original Dif (mm)
I	TCN	NW	11	2.17
I	TCN	SW	46	0.25
I	DCN	SW	22	2.85
II	TCN	NW	33	1.17
II	DCN	NW	17	-2.88
II	TCN	SW	8	4.52
II	DCN	SW	0	9.57

In this study, there were seven comparisons between the target/downwind regions and their corresponding control region: District I northwest flow target control, District I southwest flow target control and downwind control, District II northwest flow target control and downwind control, District II southwest flow target control and downwind control. There was a comparison between the target and control regions for both districts with both flow regimes, and a comparison between the downwind and control regions for both flow regimes for both districts, with the exception of District I with a northwest flow because there was no downwind region. The comparisons between the regions were then made for the months of June, July, August, and for the entire season. Only the seasonal differences in rainfall between the regions were tested for significance.

If the *p-value* calculated was 10% or greater, the null hypothesis that seeding had no affect on rainfall amounts was not rejected and the difference between the regions was determined to not be significant. The null hypothesis was not rejected in five of the seven cases. By not rejecting the null hypothesis does not mean the null hypothesis was true, it only means that there was insufficient evidence to reject the hypothesis. In four of these five cases, the original target/downwind region received more rainfall than the control region for the seasonal rainfall amounts. There was only one case when the seasonal rainfall amount for the control region was more than the downwind region, and that was for District II with a northwest flow. There were possible errors in the northwest flow cases that could have biased the results; these errors are discussed in the next sections.

If the *p-value* calculated was less than 10%, then the null hypothesis was rejected, and the difference in rainfall amounts between the target/downwind regions and the control regions was determined to be significant. This occurred in two cases out of the seven, both the target-control and downwind-control differences for District II with a southwest flow. In both of these cases the original target and downwind regions received more rainfall for the season than the control region. Based on the results, it can be inferred that seeding likely was the cause of the increase in rainfall.

Errors and Uncertainties

The analyses showed there were cases when the storm tracks had southwesterly flow and the NCEP/NCAR reanalysis wind data had northwesterly flow. It was calculated that this error between the two data sets occurred on 11% of seeded days in both districts. When the error between the data set occurred in District II with a northwest flow, the control region was downwind region of the target region and the downwind region was upwind of the target region. To understand the effects of this error, the difference between the downwind and control regions for District II with a southwest flow was examined. For District II with a southwest flow, the downwind region received 13% more rainfall than the control region and the Monte Carlo test indicated the difference was significant. Therefore, when a northwesterly flow regime was determined when the true flow was southwesterly, the rainfall amounts in the control regions would have been increased due to seeding. It was likely that this error biased the results in the difference in rainfall between the downwind and control regions for District II with a northwest flow. The true difference in rainfall between the downwind and control regions without the effects of the error in this case was unknown.

If a northwesterly flow regime was incorrectly selected instead of a southwesterly flow regime this could have also affected the differences in rainfall between the northwest flow target and control regions for both districts. The corresponding control regions for these target regions could have had increased rainfall due to seeding effects when they were downwind of the target region. This would lead to a decrease in the rainfall difference between the target and control regions.

There could also have been errors by the observers in recording rainfall amounts on the wrong day, which could have placed the rainfall in the wrong flow regime. However, this error was assumed to have a minimal effect in biasing the data. When a region's rainfall amount was calculated, all the gauges amounts in the region were averaged to obtain one value. This averaging would minimize the effect of an individual error. In addition, any such errors would probably occur randomly in all regions and so would not produce a bias.

The control region used for District II with a northwest flow was located on the northern border of North Dakota. There was a lack of gauges on North Dakota-Canada border, which could have led to incorrect climate ratios for this region. If the climate ratio was incorrect, this would have given inaccurate results in the difference between the target/downwind regions and the control region. Also, the climate ratios were based on the mean monthly total rainfall amounts. It was observed that more rainfall occurred when there was a southwest flow than a northwest flow. Since more rainfall was recorded on southwest flow days, there was a possibility that the climate ratios represented the southwest flow amounts better than the northwest flow amounts.

When testing for significance, an incorrect significance level could have been calculated due to errors in the data. By running a test a multiple number of times, it is possible that errors in the results could be multiplied and significance could have been found where there was really none, or no significance could have been found when there should have been. Without knowing the exact cause of the errors mentioned above, this issue could not be further investigated.

CHAPTER 5

CONCLUSIONS

The ND ARBCON rain gauge data was used to quantify the results of the evaluation. For each flow regime, the target, downwind, and control regions were defined, except in District I with a northwest flow where no downwind region existed. A climate ratio based on the 1931 to 1960 time period for June, July, August and the season was calculated between each target/downwind region and their corresponding control region. The climate ratio was applied to its corresponding region rain gauge data. Next, a ratio test was applied to the data to determine the percent difference between the target/downwind region with the control region. A Monte Carlo test with 1000 iterations was conducted on the data to determine the significance of the difference calculated between the regions.

Of the seasonal results, there were four cases out of seven where the target/downwind region received at least 5% more precipitation than the control. Those cases were District I northwest flow target region (6%), District I southwest flow downwind region (10%), District II southwest flow target region (8%), and District II southwest flow downwind region (13%). The other three cases were District I southwest flow target (3%), District II northwest flow target (3%), and District II northwest flow downwind (-2%). Of the greatest four cases, two were found to have been significant by the Monte Carlo test and they were the target and downwind regions for District II with a southwest flow. There was only one case where the control region received more precipitation than the target/downwind, which was the downwind region of District II with a northwest flow.

The northwest flow regions contained errors due to the NCEP/NCAR wind data indicating northwesterly flow when the storm tracks data had a southwesterly flow regime. For both District I & II, the NCEP/NCAR wind data classified 11% of the days seeded as a northwest flow day when the storm tracks data had the storm flow from the southwest. This resulted in the control region being biased by seeding. The amount of error was unknown, but was thought to have affected all the northwest flow cases.

Given that all of the southwest flow cases received more rainfall than the control regions, this study concludes that cloud seeding in western North Dakota likely increased precipitation. Four of the southwest flow cases received from 3% to 13% more rainfall than the control regions. These results are similar to previous studies of 5 to 10% increase in areas affected by seeding. The two southwest cases for District II showed a significant difference between the target/downwind regions and the control regions.

One recommendation is being made for future precipitation evaluations conducted on the NDCMP using the ND ARBCON data. It is recommended that NWS gauges in Montana, immediately west of District I and II, be used for control region data. Partitioning between southwest and northwest flow cases would no longer be needed and each district would have a single target, control, and downwind region. The southwest and northwest flow cases were used in the current study because of the control regions having to be located north and south of the target region. This change would permit a more-complete evaluation since downwind areas would not have to be limited in size in order to create control areas. The NCEP/NCAR wind data would then be used to distinguish only between easterly and westerly flow. There were relatively few cases noted when the NCEP/NCAR wind data incorrectly distinguished between easterly and westerly flow regimes, as compared to distinguishing between northwest and southwest flow regimes, which would reduce the possible control region bias encountered in this study. The radar storm tracks data would still be used to determine the NCEP/NCAR wind data that best represents the storm motions.

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