SNOW EXTENT AND DEPTH OVER CENTRAL NORTH AMERICA:

1966 - 2018

by

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ABSTRACT OF THE THESIS

Snow Extent and Depth Over Central North America: 1966-2018

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Snow extent and depth climatologies are presented for central North America in a region situated east of the Rocky Mountains from the Texas Panhandle to Southern Alberta. Daily surface observations from United States Cooperative Observer Program (COOP) and the Meteorological Service of Canada's stations are used over the study period of 1966-2018. Using a quality-controlled gridded database, the spatial characteristics of extremes, season length, and snow depth are examined. Past studies have primarily focused on snow cover extent, with few including depth analyses. Adding depth to the more traditional examinations of extent allows for a more thorough evaluation of the region's snow climatology and permits a better understanding of snow cover and associated relationships with hydrological, societal and other climatological variables.

Annual average maximum across the study area range between 2 cm to 68 cm, with peak depths varying from December 10th in the south to February 26th in the north.

Average season length, defined as the longest run of snow depth of 7.6 cm or greater and at least seven days in length, varies between 10 to 135 days. A snow depth trend analysis for the 52-year period shows decreases in the coldest part of the year with the largest decreases being in the north. The downward trend is most pronounced at greater depths. In most months, depths have a larger percentage decrease than extent. Many analyses of depth are interested in understanding snow water equivalent over mountainous area, but few studies have focused in areas such as central North America, despite being of importance here too. Evaluating depth provides a more complete understanding of the impact of snow cover on the environment than simply looking at extent. This includes a better estimate of surface albedo, insulation of the underlying soil, and the snowpack water content. Thus, knowledge of snow depth contributes to a better understanding of ephemeral snow's role in North America's Plains and Prairies climate, as well as earth's climate, atmospheric circulation, ecological systems, weather forecasting and flood prediction.

Acknowledgements

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Table of Contents

List of Figures

List of Tables

Chapter 1: Introduction and Background

1.1 Introduction

Snow cover has a substantial impact on climate throughout the winter season that has implications for the entire year. Impacts include the effect of snow on the surface energy balance, as well as factors such as soil moisture, soil temperature, and flood risk and prediction. Snow cover alters the global surface energy budget by changing the amount of incoming solar radiation absorbed by the surface by reflecting sunlight off the surface, much of it returning to space (Kunkel and Palecki et al., 2007). Snow on the ground acts as an insulator for soil beneath the snow by disconnecting it from the potentially colder air above the snow layer. This disconnect is largely dependent on the snow depth, which also affects soil moisture thus water resources for humans (e.g. agricultural) and ecological systems (Dyer and Mote, 2006). The impacts of a warmer climate on the cryosphere are rather clear, with reductions in the extent and quantities of snow, ice and permafrost already recognized (IPCC AR 5). However, questions remain regarding associations between a changing cryosphere and other components of the climate system, including precipitation and atmospheric circulation. These issues will likely vary from one region to another, as the amount of snow on the ground at any time and place depends on such factors as air and ground surface temperature, precipitation intensity and even winds blowing the snow.

1.2 Research Objectives

The main goal of this study is to examine snow depth and extent over the US Great Plains and southern Canadian Prairie. The first objective is to develop a climatology of snow depth for the 52-year period from 1966-2018. With a climatology established, analyses of the spatial and temporal variability of snow depth and snow extent will be conducted. This includes analyses of spatial and temporal patterns of depth and extent on regional to sub-regional scales. Earlier studies have explored snow cover over central North America (Robinson and Hughes, 1991; Hughes and Robinson, 1995), although none have examined snow extent and depth since Dyer and Mote (2006).

This study includes the following objectives:

1. Develop a climatology of snow depth within central North America using in-situ observations from Cooperative stations in the United States and Canada. Included are:
    a. Annual, monthly and daily means and extremes.
    b. The timing of the annual average maximum snow depth.
    c. The percentage of days above various snow depths.
    d. The average first/last days above given threshold depths.
2. Conduct time series analyses of snow depth within the region over the 50-year study period. Address the following questions:
    a. Have there been any trends in snow depth within this region?
    b. How has the duration of various snow depths varied over the study period?
    c. How do any changes in depth compare to changes in snow extent?

1.3 Background

It is estimated that two billion people rely on the snowpack runoff into 97 basins around the world for drinking water (Mankin et al., 2015). Human water consumption is not the only importance of a snowpack. The amount of snow and the timing of snowpack melt contribute to the health of agricultural production. A shallow snowpack will result in soil that lacks much needed insulation and moisture. Also, with less snow stored in mountain regions, there will be reduced streamflow downstream toward populated areas and agricultural ones too. Snowmelt also contributes to devastating flood events, such as the 2019 flooding in the midwestern United States and multiple flooding events along the Red River of the North, resulting in expensive damage and even fatalities.

Snow cover is highly variable across North America. Snow, to fall and accumulate, requires a source of moisture as well as temperatures at or below 0°C. The amount of snow that falls depends on large scale atmospheric conditions transporting moisture into a region. Once on the ground, the depth and duration of snow cover is determined by a combination of factors such as the amount of incoming solar radiation, soil temperature, and air temperature. Other factors such as differences in elevation and distance to a water body, and large-scale atmospheric patterns such as the North Atlantic Oscillation (NAO) and the El Nino Southern Oscillation (ENSO) have major influences on where and how much snow is on the ground.

Within many middle and high latitude regions, snowfall and resultant snow cover are seasonal phenomena that have important physical and societal implications. Snow has a direct impact on the surface energy balance and atmospheric chemistry (Richardson et al. 2013). Warmer average temperatures will likely indicate more precipitation falling as rain instead of snow, decreasing the accumulation of snow depth throughout the season.

The 2014 National Climate Assessment suggests that, on average, across the United States precipitation has increased overall by 5% (NCA, 2014), but this does not differentiate whether the precipitation has been in the form of rain or snow. It also does not give a big picture of how snow is changing across the entire Northern Hemisphere.

The Northern Hemisphere is important to snow climatology because of the large area of land cover, compared with the southern hemisphere, this results in the Northern Hemisphere having a larger impact on surface albedo. From the 2013 IPCC cryosphere assessment report, snow cover extent in the Northern Hemisphere has decreased, particularly in spring (IPCC AR5, 2013). Snowfall measurements are limited to only low elevation, open vegetation areas and rely heavily on in situ measurements (IPCC AR5, 2013). Changes in snowfall amounts have varied by region across the Northern Hemisphere with decreases in snowfall found in southwest Alaska but increases in snowfall in the Great Lakes region (Kluver et al., 2015).

Snow extent can be monitored via remotely sensed imagery from satellites and aircraft as well as observations on the ground, the latter especially where dense networks of observations exist. Snow depth reports require in-situ observations or advanced remote sensing techniques that have only shown limited success in estimating snow mass (converted to depth via algorithms that assume a given snowpack density). Snow depth has been measured by human observers in an organized manner for well over a century. In the United States, abundant observations have been available in digital format since 1948, with the density of observing stations particularly pronounced in lower elevations. This includes our Central Plains study region. In Canada, station observations are mainly situated within a few hundred miles of the U.S. border and are best available in digital format since the 1960s (Dyer and Mote, 2006). Thus, this study starts in 1966, chosen to coincide with the establishment of the weekly satellite derived snow cover extent mapping.

Extent can provide an understanding of local cooling from reflectivity, but extent alone does not give an indication of the water content within the snowpack. Snow depth expands on this, providing an estimate (based on estimated density or direct measurement) of water content which has implications concerning water resources, surface energy and moisture budgets, soil processes, and ecological systems (Dyer and Mote, 2006). The depth, longevity, and timing of snow cover as the climate changes is uncertain. Dyer and Mote (2006) in an analysis of snow depth and extent at different threshold levels for North America found that snow cover was decreasing in both extent and depth. The highest changes in depth were found in the regions of deepest snow. This study also found that the greatest decrease in snow depth under 20 cm was found in the Northern Plains between 1980-2000. This study will not only expand the record through 2018, it will also look, in detail, at patterns within the central North American plains and prairie.

Developing climatologies of snow depth and extent will further understanding of trends and variability of snow in the vertical and horizontal dimensions. Using extent with depth data also allows for an analysis of extent at various depths, something not possible from just looking at extent.

1.3.1 Snow's Influence on the Surface Energy Balance

Those who have experienced snow will notice the most distinguishable feature of fresh snowfall is the brightness. After a snowfall event, the snow on the ground is a near perfect white color, which reflects sunlight in all directions. Snow on the ground during the daytime reduces shortwave radiation because of high surface albedo (Namias, 1985). The reflected sunlight is unable to reach the darker soil beneath the layer of snow and become absorbed, thus snow has the effect of cooling the surface and subsequently the lower atmosphere. Figure 1.1 provides a detailed visualization of the processes involved when snow is present (Marks et al., 1998).

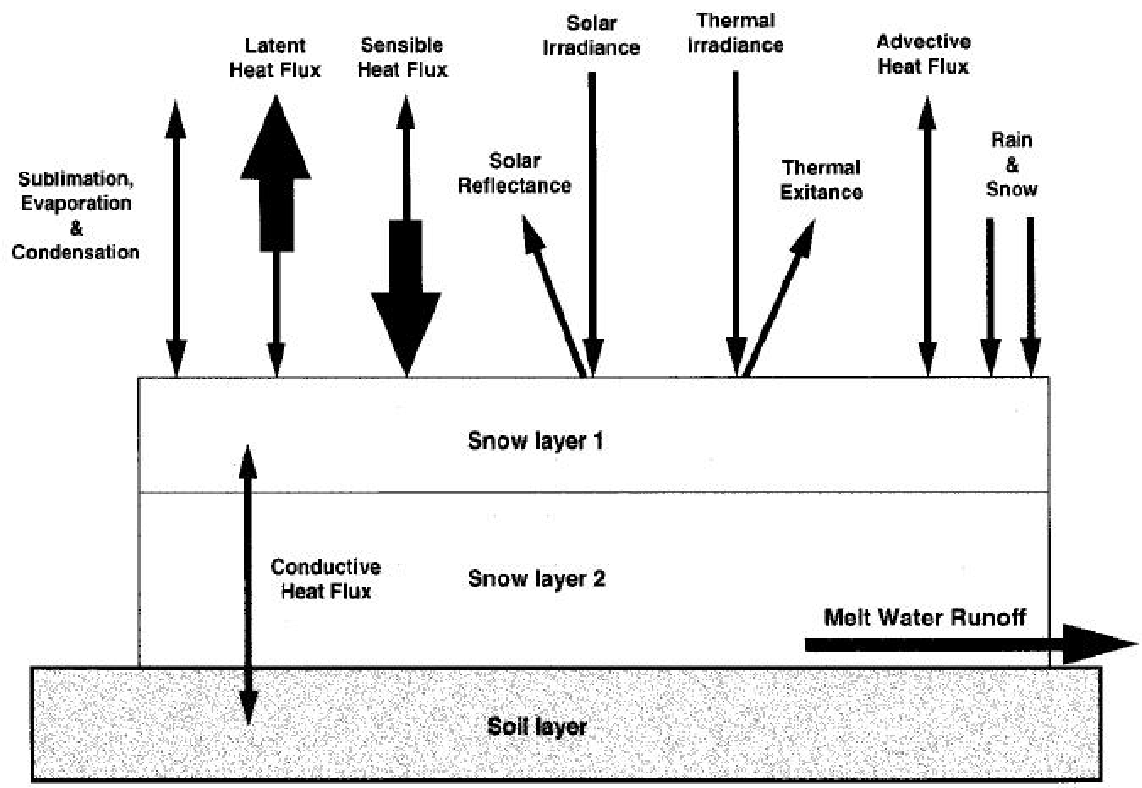

Figure 1.1. From Marks et al. (1998), this schematic shows the processes involved in snow melt as well as other features of the surface energy balance. Another notable aspect of this schematic shows the influence snow has on the soil layer below.

Several studies have proved empirically the influence of snow on surface air temperature, including Leathers and Robinson (1993) observing that temperatures across North America are lower in years where the snow cover was above normal. On the other hand, during periods of below normal snow cover, temperature was observed to be above normal. This is related to the radiation exchange between the surface and the atmosphere, which accounts for large scale variations. Studies involving snow cover have to take into account fluxes in the energy balance, including radiation exchange, sensible and latent heat fluxes as a result of, “turbulence in the boundary layer above the snow surface, the ground heat flux, and the energy transfer resulting from rain or snow” (Male and Granger, 1981). The seasonality of snow within a large mid-latitude area, such as central North America, is a topic of interest for many who want to better understand the responses of a changing climate.

Climate models are influenced by our understanding of the surface energy balance. Since snow cover has such a major seasonal role on the surface energy balance, models must account for the regional components of snow cover. Cover is not evenly spread across an entire continent and sometimes even regionally, which makes it difficult for climate models to accurately model snow depth and snow extent. Allan Frei in his book review of *Snow and Climate: Physical Processes, Surface Energy Exchange and Modeling,* highlights snowpack as “a layer of finite vertical dimension that modulates the energy and mass exchanges between the surface and the atmosphere” (Frei, 2009). This suggests the importance of developing a snowpack climatology to permit patterns of snow depth and melt to be discerned, which in turn can be related with other model components.

1.3.2 Study Region

The Central Plains of the United States and the Canadian Prairie cover an area of roughly 4 million km^2, most of which is used for agriculture. Within the United States, eight of the top ten states in agricultural production are located within the central United

States. These states include Iowa, Texas, Nebraska, Minnesota, Illinois, Kansas, Wisconsin, and Indiana (USDA, 2017). In Canada, the provinces with the most area used for farmland are all within the Prairie and include Saskatchewan, Alberta, and Manitoba (Census of Agriculture, 2016). Much of central North America relies on snow as an important hydrologic and economic resource. The Great Plains and Prairie are subject to widespread droughts that negatively impact agricultural production. While irrigation is an option for some farmers to reduce the effects of drought, most still depend on precipitation to provide water. In this region, it is estimated that snowfall is twice as valuable as rain as a resource for agriculture (Hughes, 1993).

Our study region is defined as the portion of North America from Edmonton, Canada in the northwestern to Huntsville, Alabama in the southeast. The opposite diagonal of the study area stretches from the Panhandle of Texas in the southwest to southern Alberta. The area of each cell and the average elevation is presented in figure 1.2. The northern boundary in Canada results from a much lower density of stations to the north (discussed further in a later section).

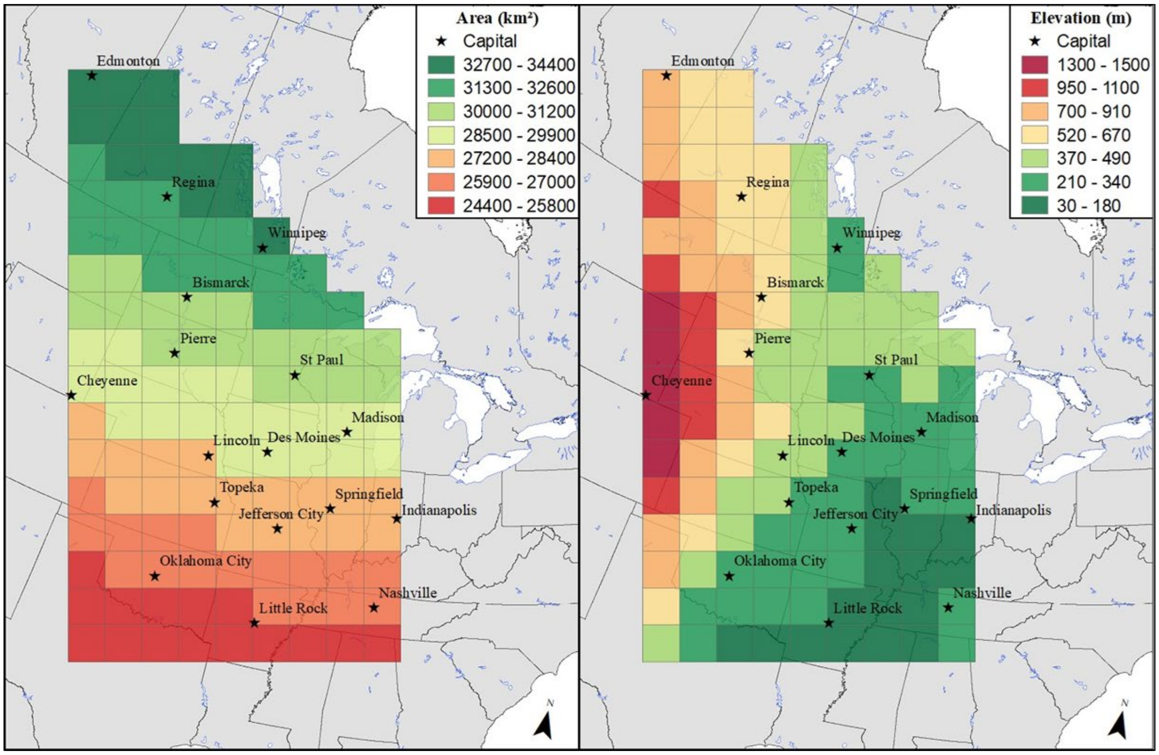

Figure 1.2. Study area defined by grid areas (square kilometer) (left) and by average elevation, (meters), from the US Navy Fleet Numerical Meteorology and Oceanography Center Global Land (10-minute) DEM from TerrainBase at NCEI (right). Maps include capital cities of states and provinces found within the study area.

The study area is characterized by relatively consistent surface characteristics of generally flat open lands with little tree cover.

Previous studies have looked at patterns of snow extent in the Northern Hemisphere (e.g., Kluver et al., 2015; Estilow et al., 2015; Robinson and Frei, 2010). Within central North America, the biggest difference in snow extent is by latitude with higher latitudes generally having more months with snow cover compared to low latitudes. The longitudinal extent of snow is then determined by factors associated with elevation, precipitation distribution, and distance to bodies of water.

Snowfall in this study region is mainly a result of synoptic patterns as opposed to being influenced by orographic effects, lake effect or ocean-land interactions. The source of individual snowfall events is beyond the scope of this study, but it is important to put into context where the snow in this region tends to originate from as it helps define some of the characteristics of the regional snowpack. Colorado Lows and Alberta Clippers tend to most commonly produce snowfall, but there are other "hybrid" patterns that contribute snow (Kennedy et al., 2019). All these synoptic winter storm patterns affect the characteristics of the snowpack. Also, the timing of these events varies seasonally. Depending on the storm, each of these patterns produces a snowpack of varying density. Wetter snows tend to have a higher density and compact more than dry snow, impacting snow depth. Differences in snow density change the amount of water stored within the snowpack, making modeling of the Snow Water Equivalent (SWE) a challenge. SWE, being the measured amount of water in a snowpack if melted instantaneously ("What is Snow Water Equivalent?"), depends on the amount of snow, the air temperature and any refreezing that may have taken place (Bormann et al., 2013). These estimates are important to those who depend on seasonal snowmelt as a source of drinking water.

Synoptic atmospheric circulation patterns also have an impact on temperature and moisture within the region through the transport of warm air from the Gulf of Mexico, or cold arctic air masses. Snow depth patterns tend to correlate with temperature with less snow in regions with warmer temperatures. Cooler temperatures maintain the snowpack until the next snowfall, while warmer temperatures will add energy to the surface that will reduce the snowpack (Dyer and Mote, 2006). Snow depth is sensitive to variability in the surface energy balance as a result of temperature variations, but these changes in snow depth cannot be attributed solely to temperature changes.

Chapter 2: Data and Methodology

2.1 Introduction

This chapter is divided into three sections. The first introduces study data, the second quality control techniques, and the final section explains threshold depths used for this study. The study period is defined as July 1st, 1966 through June 30th, 2018, with the beginning and end of the "Snow Year" being selected as the portion of the year least likely to receive snowfall. Any snow depth reports in July and August were removed for analysis because snow in this region is not likely during these months, thus these are likely reports of hail on the ground.

2.2 Data

Data employed in this study are from observations gathered by weather observers within the U.S. National Weather Service's Cooperative Observer's Program (COOP) and the Meteorological Service of Canada's Cooperative Climate Network (CCN). Cooperative stations are maintained by volunteers who make daily observations of maximum and minimum temperature and precipitation (liquid and frozen). These stations have the benefit of being greater in number than only official government weather stations, which are mainly located at airports, thus providing more complete spatial coverage (National Weather Service, 2019). Cooperative observations of snow use "ruler" measuring method where snow measurements are taken once a day and averaged to minimize the impact of blowing snow (National Weather Service, 2013). The reports taken are rounded to the nearest whole inch and observers are also instructed to report a value of "0" on days with no snow cover. These stations tend to be in open clearings near the station, away from tall vegetation and buildings to maintain a level of consistency among stations.

This study is a collection of these in-situ station observations of snow depth in the United States and Canada, from January 1966 to December 2018 using a dataset containing observations of snow depth (reported in mm) and snowfall (reported in cm) originally gridded into a 1° latitude x 1° longitude product by Kluver et al. (2015). This dataset was regridded to a resolution that matched the NOAA Weekly Snow Cover Extent (SCE) for comparison and validation study that is not discussed here. The regridding process consisted of an interpolation of data onto a spherical surface that was then projected onto a Cartesian plane using an inverse-distance interpolation algorithm to produce an 89x89 polar stereographic projection with a central meridian at -80. The final product provided a daily average snow depth and the number of reporting stations with greater than 0 mm of snow depth for each cell (Mote and Robinson, submitted).

The maximum number of reporting stations within each cell ranges between 5 and 160 stations (figure 2.2). Of the cells included in this study, station data was consistent, varying little over the course of the study period. It should be noted that the number of reporting stations within a cell does not dictate the quality and consistency of observations for a cell. For example, cells in the southern plains of North America that had just five maximum reporting stations, but observations are among the most consistent of all cells, having few missing observations.

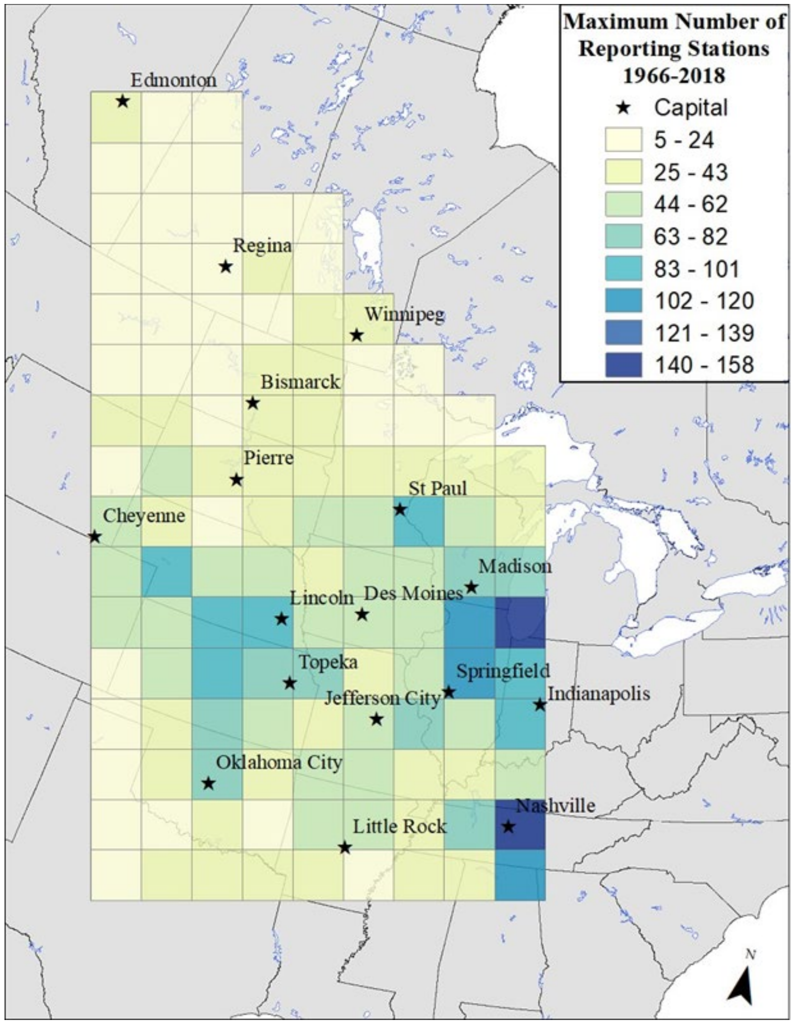

Figure 2.1. Maximum number of stations reporting snow depth on a single day from 1966-2018. Darker colors show cells with the most reporting stations.

2.3 Quality Control

A detailed quality control was implemented to refine the study area to cells with consistent observations over the 52-year period (Figure 2.2). Cells that had more than 15% days with missing data were excluded from the study, such as cells located in northern Canada.

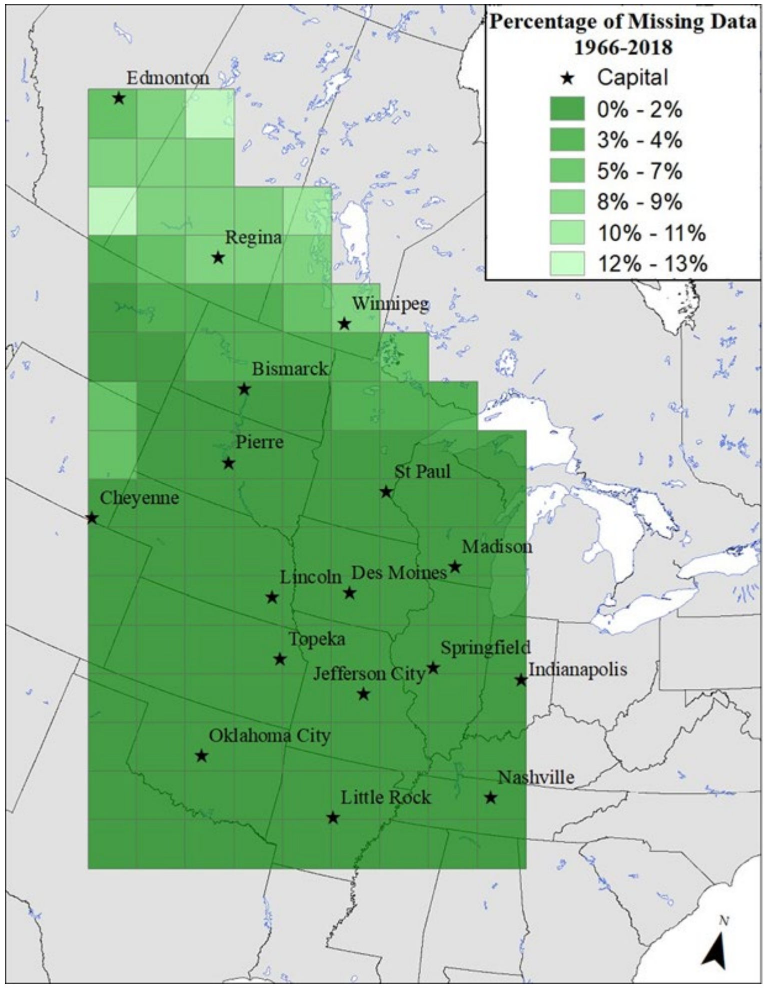

Figure 2.2. The percentage of days with missing observations within cells over the 52-year study period.

Measurements of snow depth have gone through initial quality control at the National Centers for Environmental Information (NCEI). Another quality control method used for the dataset was an examination of extreme value thresholds (Mote and Robinson, submitted 2016). Even with these methods employed there were still questionable observations for a study of this level of detail. Thus, further quality control was conducted as follows:

1. Each day that snow depth was reported had a corresponding snowfall report. With this snowfall data, any increase daily in snow depth that was not accompanied by

measurable snowfall greater than 0mm was deemed erroneous and the observation for that day was considered missing.

2. Any unusually large single day snow depth increases were identified where snow depth reports exceeded the previous days depth by more than 750mm (29.5in). They were flagged and not used, as these reports exceed each state and provinces record single day snowfall (SC ACIS2).

3. A consistency standard was implemented by identifying snow depth observations surrounded by days with missing values. To accomplish this, observation that had two missing reports before and after a non-missing observation were flagged and considered to be missing as well. This was done to remove questionable observations that were surrounded by blocks of missing data.

2.4 Data Processing

The computer software used for processing includes Fortran 90 with BASH Programming, Python and ArcMap10.7. The workflow process is shown graphically in figure 2.4.

Fortran 90 is a computational programming language capable of processing large amounts of data efficiently. All the data were first run through a Fortran 90 program which was able to separate the data, by cell into its own spreadsheet. The data, once in a format that could be easily parsed, was then processed within this program to make all the initial calculations, such as averages, extremes, etc. This program had a companion BASH Programming script to improve the efficiency of the program. BASH Programming has the advantage of being able to process all the grid cells within the same program without having to restart the script for each new cell. This increases the efficiency of the data processing while also eliminating any human interaction while the program is running.

Once the Fortran 90 program produced output, it was imported into Python or ArcMap to produce figures. Python is a powerful coding language meant for data processing and the creation of graphics. For this reason, Python was used to make all figures in this study using an add-on module named Matplotlib. ArcMap on the other hand is a mapping software used to display data spatially and create the maps seen in this study. This code is provided to the public via GitHub as open-source tools.

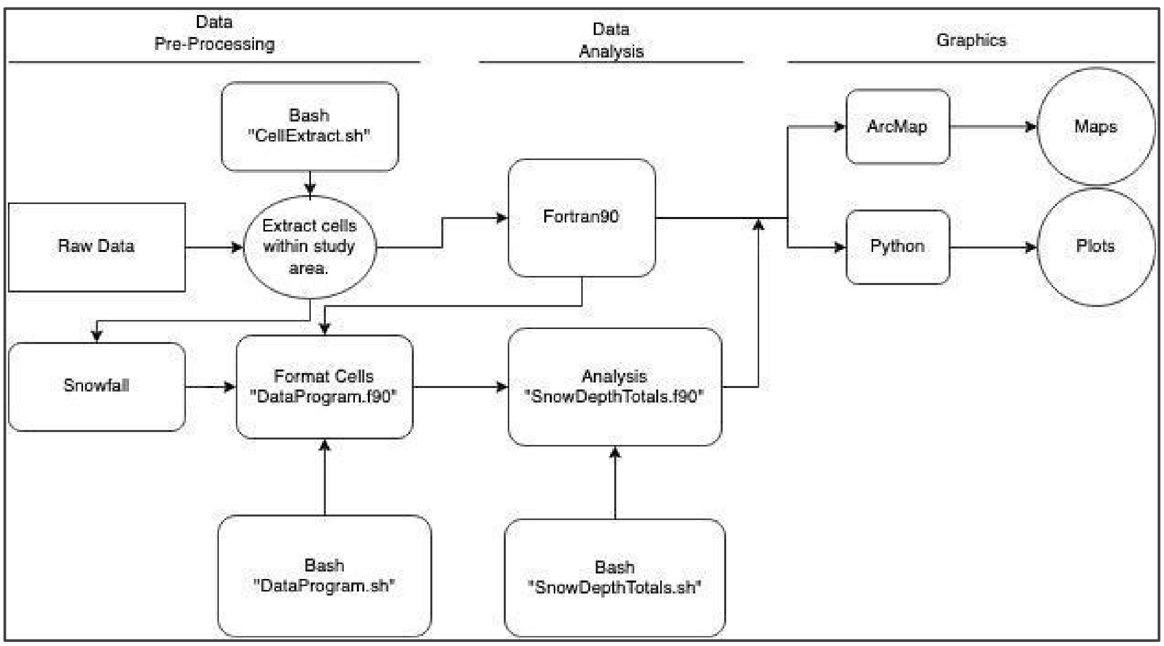

Figure 2.3. Workflow of the data processing methodology for this study. The three sections include "pre-processing," "data analysis," and "graphics". Details of scripts and code can be found in a GitHub repository (https://github.com/Logan-Soldo/SnowDepth).

2.5 Snow Depth Threshold Values

Over the course of this study, threshold depths of 7.6 cm(~3in) and 2.54 cm(1in) are used. A threshold depth of 7.6 cm is used, as it is assumed that the entire surface will be covered with snow at this depth (Robinson, 1991). Observational measurement biases at shallower depths introduce uncertainties as to whether the area surrounding the measurement site is fully or perhaps only partly snow covered. For snow extent, depths greater than or exceeding 2.54 cm are used. While this dataset uses averaged snow depth reports, this depth is consistent with observations in the United States where it is common for observers to round their measurements to the nearest whole inch (“Co-op Weather Observation Quick Reference Guide”).

Chapter 3: Snow Depth Climatology

3.1 Sub-Regional dimensions:

To begin studying the snow depth climatology of the study region, a count of the number of days with snow depth averaging 7.6 cm or greater was generated for each study grid cell for each month. These values were used to define sub-regions within the overall region by generating monthly cover percentages and binning results according to quartiles. As shown in figure 3.1, patterns arose that assisted in dividing the region into four distinct subregions as shown in figure 3.2.

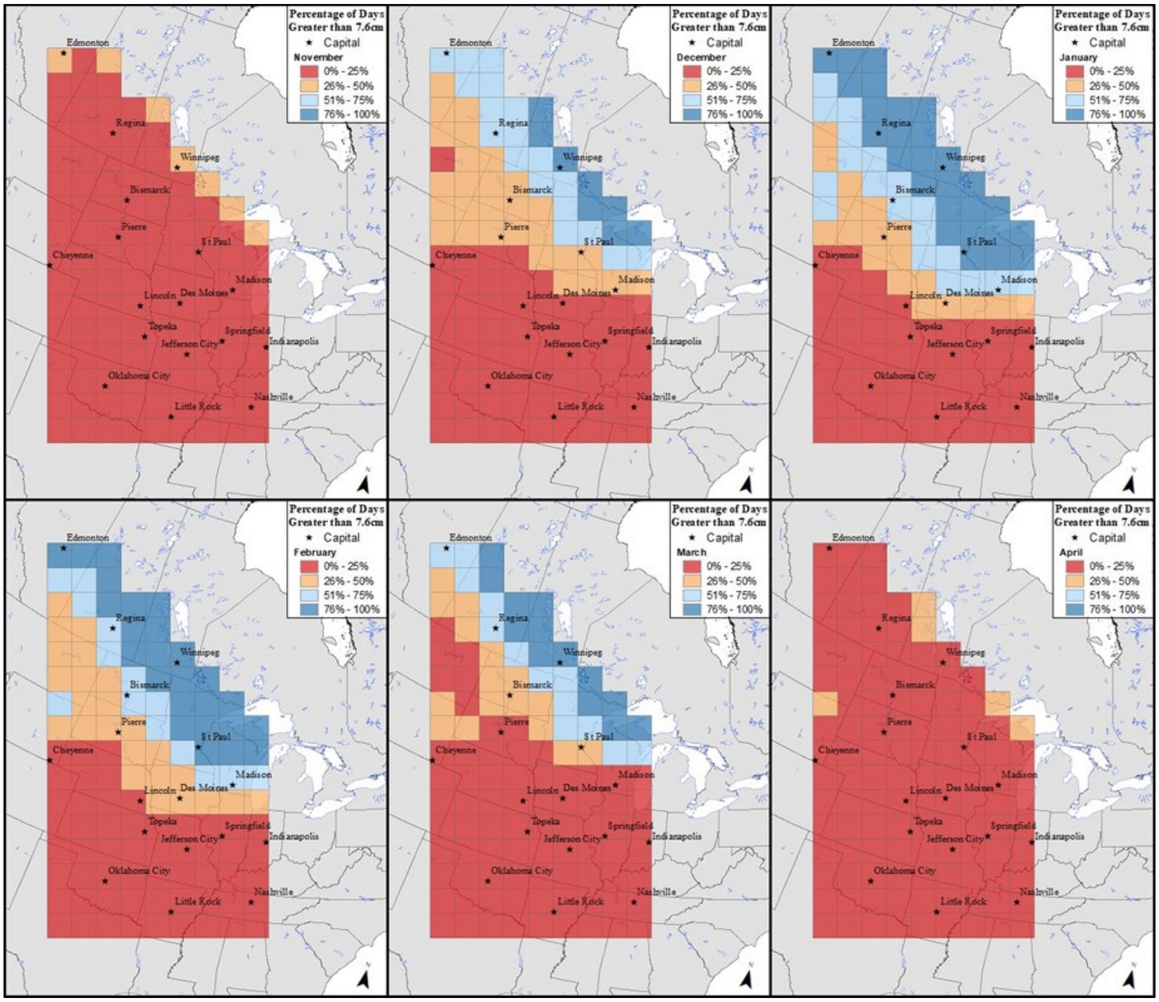

Figure 3.1. Percentage of days with a snow cover of at least 7.6 cm shown by month. Top from left to right: November, December January. Bottom from left to right: February, March, April.

The monthly analysis (figure 3.1) shows little coverage in the "shoulder months" of November and April with developing coverage in December, ending quickly in March. The December through March maps suggest that four sub-regions are appropriate for evaluation. Figure 3.2 averages these months and confirms this distribution. The cells south of a line roughly between Cheyenne, WY, Lincoln, NE, Des Moines, IW, and Springfield, MO are defined as subregion 1. On average, the cells in this subregion spend every month below the 25% threshold for the number of days above a depth of 7.6 cm. This was the largest subregion in the study area, with 59 cells, half of the entire study region. Sub-region 2 covers 23% of the study area and stretches across an area as far north as southern Alberta and Saskatchewan in the west and Madison, WI in the east. The smallest sub-region (sub-region 3), contains just 12% of the cells in the study area, including an outlier cell in northeast Wyoming. Covering 15% of the study area, the northernmost sub-region 4 contains the deepest depths, with coverage of 75-100% between December 1st and March 31st. This sub-region also experiences very little variation between January and February. Another notable feature of this subregion is the minimal change between December and March. The difference between these two months is the expansion of the sub-region further west as the year progresses.

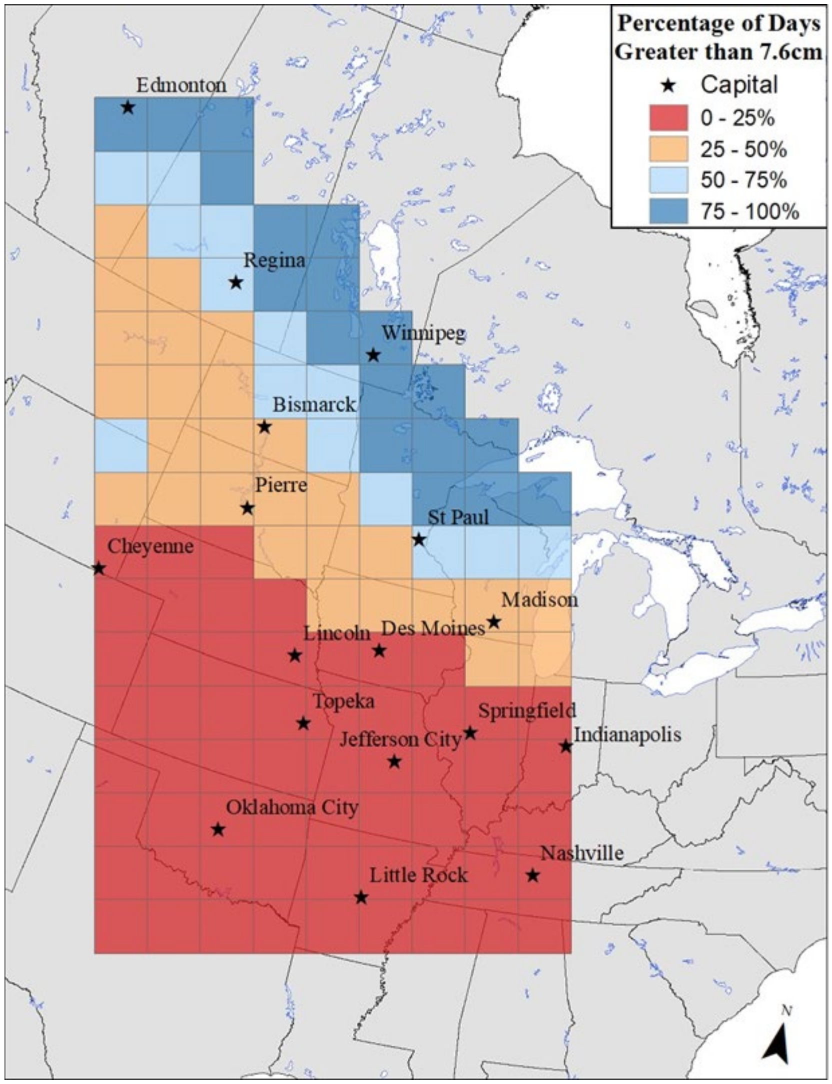

Figure 3.2. Average percentage of days with a snow cover of at least 7.6 cm during from December through March. The four sub-regions are defined by percentage quartiles of 0-25% (Region 1), 26-50% (Region 2), 51-75% (Region 3), 76-100% (Region 4).

3.2 Seasonal Depth Progression

With subregions defined, the progression of depth throughout the year is investigated for each. Daily depths for each cell in a subregion are averaged and results displayed in figure 3.3. A well-defined seasonal progression of snow depth is recognized in each subregion as are distinct differences in daily depths between the subregions. This provides further support for the four-subregion division. Subregions 2, 3, and 4 all tend to show a sharp increase in snow depth followed by a plateau through the late winter into early spring. Sub-region 1 is more variable than the other three with a steadier increase in depth followed by a brief plateau of around 1-4cm starting prior to the new year. Subregion 2 experiences two plateaus. The subregion also experiences a two week decrease in snow depth from mid to late February, with depths decreasing from 12cm to 9cm. Subregion 3 experiences an average maximum depth around 22cm, and like Subregion2, has two plateaus with a more gradual decrease to a second plateau than found in subregion 2 Snow accumulation starts earliest in subregion 4 and ends the latest. Depths also exceed those in the other regions throughout the season reaching an average maximum depth of 33 cm at various points in the winter. This subregion continues to increase to a plateau while Subregion 3 depths slowly begin to decline. Subregion 4 later experiences the fastest decline in snow depth, something of concern regarding potential river flooding.

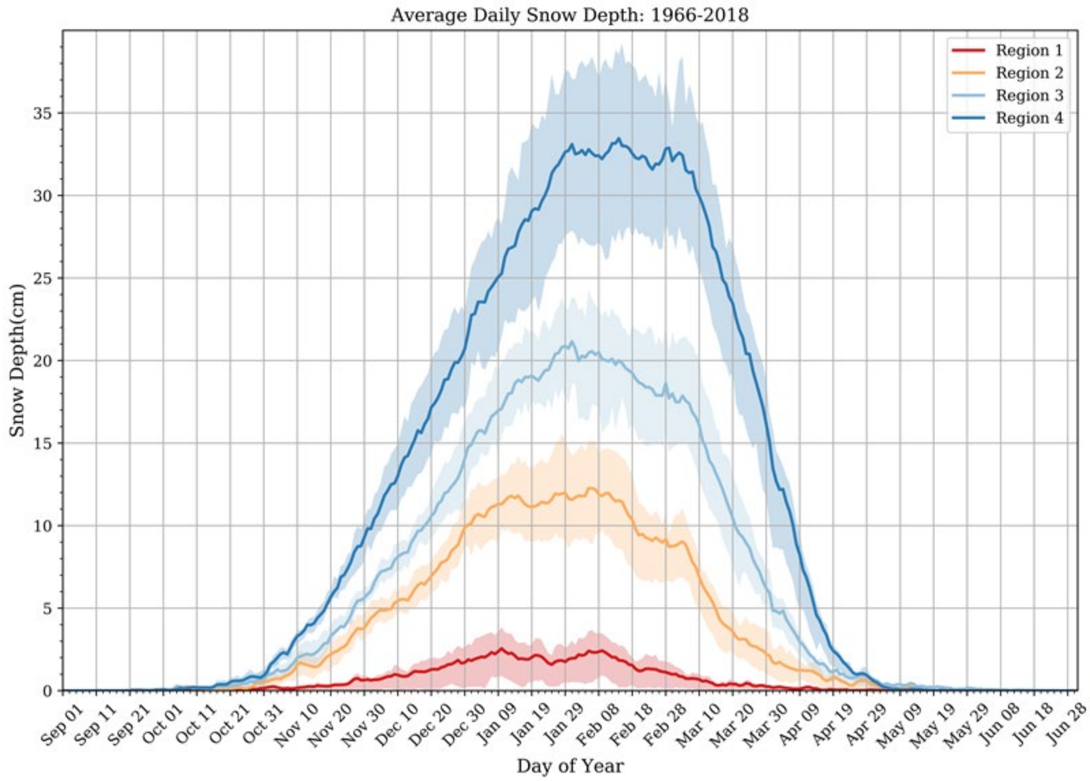

Figure 3.3. Average daily snow depth for each of the four subregions. The solid line shows the average daily depth within a subregion during the course of the snow season. Shading represents the 25th and 75th percentile limits. Leap days are removed for this analysis.

3.3 Threshold Depths

Along with the 2.5 cm and 7.6 cm depths previously mentioned, other threshold depths are evaluated, including 15.2 cm (6 in) and 25.4 cm (10 cm). The percentage of days with snow depths above a threshold depth for the entire period between December 1st to March 31st are calculated on a per-cell basis and then averaged by the defined subregions, presented in Table 1. As expected, northern cells experience deeper depths, with more than half the winter season spent above 15.2 cm. In region 3, half the season exceeds 7.6 cm; in region 2, over half of the days are above 2.54 cm. Meanwhile, only 13% of the days exceed 2.54 cm in region 1.

Snow Depth cm	Region 1	Region 2	Region 3	Region 4
2.54	13%	57%	81%	94%
7.6	6%	37%	63%	85%
15.2	2%	19%	40%	67%
25.4	0%	8%	19%	42%

Table 1. Percentage of days above threshold depths within each region from December through March.

3.4 Season Length

The length of the snow season was generated for each grid cell, by defining length as the period from the first day of a seven-day cover of at least 7.6 cm to the last day of any cover of 7.6 cm in an individual run. Should the cover fall below 7.6 cm on any day, the run ends and perhaps later another run will begin. For this analysis only the longest run of any season is used. Again, should there not be at least one run of seven days of depths of 7.6 cm or greater in a cell during a season, a season length of zero is recorded. Also, at least five years of the 52-year study period must have a seven-day or greater run to be considered in the regional evaluation that follows.

The season length (figure 3.4) shows a general south to north gradient of increasing season length ranging from 10 to 135 days. Again, as also seen in the four subregion results above, there is a northwest to southeast angled distribution of season length. In this portion of the study, six season length subregions are defined. This pattern is disconnected between eastern Montana and northern Iowa, where the cells with a season length between 61-85 days stretch into the southwest splitting the cells with season length between 36-60 days. An outlier cell in northern Wyoming falls into the second longest season length classification, likely due to its high elevation compared to surrounding cells.

19% of the region does not meet the above stated criterion for season length, not surprisingly being the southernmost cells. The shortest season lies just to the north, with a length of 10-35 days and covers 26% percent of the entire study region. Progressing north in 25-day increasing season increments finds 11% of the region at 36 to 60 days, 18% from 61 to 85 days, 14% from 86-110 days, and the longest season 111 to 135 days in 12% of the region. The ground in this northernmost area is covered by snow of 7.6 cm or more from between 32% and 37% of the year while areas with the shortest season only spend between 3% and 8% of the year covered.

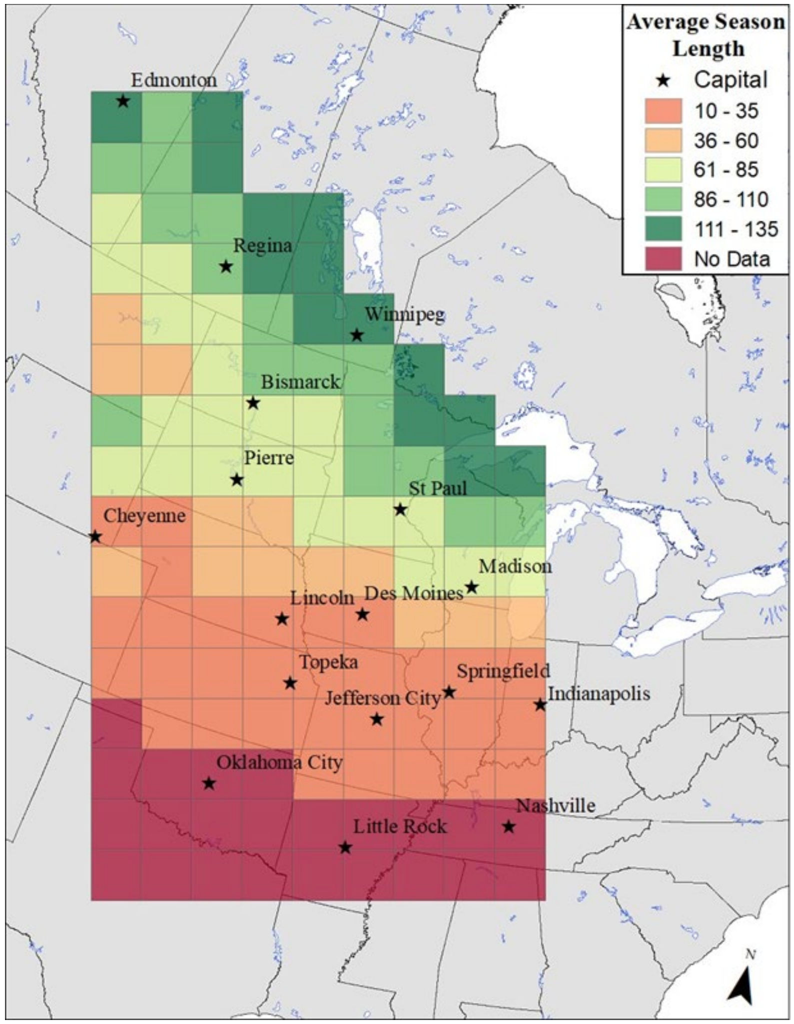

Figure 3.4. Average length of the snow season across the study region. Based on the length of time between the first and last occurrence of an average depth of 7.6 cm or greater for a cell.

The average first and last days of the snow season, again defined according to the seven-day 7.6 cm depth criterion, are plotted in figure 3.5. Both the start and end dates reveal a similar angled pattern as noted in all previous analyses. As defined in 14-day increments, the earliest start to the season is between November 23rd and December 7th in the zone lying from Alberta southeast to northern Wisconsin and the western upper peninsula of Michigan. Progressing generally to the south, the next zone is the largest and includes the cities of Bismarck, ND, St. Paul, MN, and Pierre, SE. The season commences in these cells between December 8th and December 22nd. The next zone to the south is not as well defined as others and starts between December 23rd and January 5th. A rather broad zone that runs through southern Nebraska, Kansas, Missouri, Illinois and western Kentucky has a January 6th-20th start. Two cells have a late start between January 21st and February 3rd.

The season ends in a somewhat similar spatial pattern that appears somewhat better defined than the start of the season. As defined in 18-day increments, the latest end of the season is in the northeast, from Edmonton to Northern Michigan, ending between March 22nd and April 8th. Progressing south shows a zone of similar size, including the cities of Regina, SK, Bismarck, ND and St. Paul, MN with end days between March 4th and March 21st. This zone also includes two cells in eastern Wyoming split by a zone with end dates between February 16th and March 3rd, once again resembling a similar size and shape as the previous northern zones. The next zone to the south, ending between January 29th and February 15th, is the largest and stretches from Wyoming to Kentucky and includes the cities of Lincoln, NE, Des Moines, IW, Topeka, KS, Springfield, MO, and Indianapolis, IN. This zone also includes two cells in south eastern Montana. The earliest end of the season falls within the previous zone and includes ten cells, ending between January 10th and January 28th, earlier than the start of the season for some cells in the overall region.

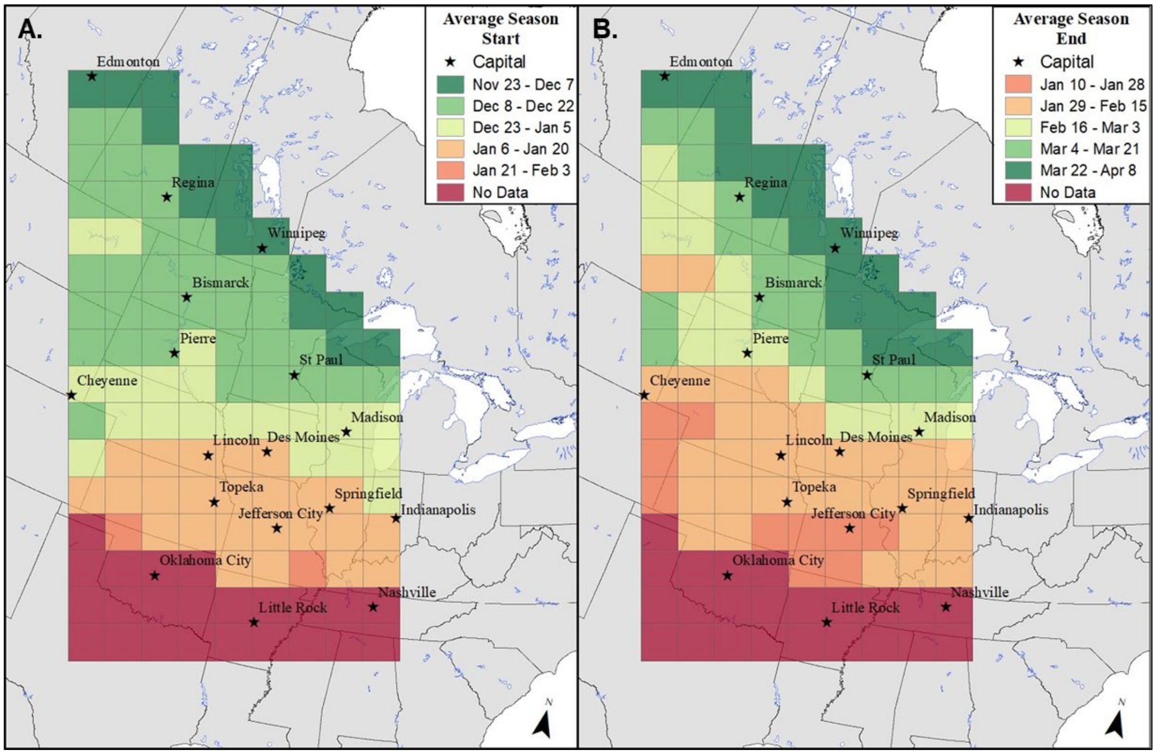

Figure 3.5. (A) Average start of the snow cover season(depth of at least 7.6 cm) divided into 14-day increments. (B) The average end of the season divided into 18-day increments. Cells that did not meet the seven-day 7.6 cm criterion are marked as "no data".

3.5 Spatial Representation of Extremes

The largest annual snow depth in each study cell was averaged over the 52-year study period to obtain climatological values. So, too, was the average date of the greatest depth similarly derived. Results for each are shown in figure 3.6. Like previous analyses, the overall pattern shows an angled increase in depths from southwest to northeast with the distribution of maximum snow depth following a pattern of increased snow depth progressing to the north (figure 3.6a) in increments of 12 cm in a range of 2 cm to 68 cm. The shallowest maximum depths are seen in the southernmost zone stretching from southern Wyoming to Northern Alabama and Mississippi reaching an average annual maximum of 2-15 cm. To the North of this zone, the largest zone with depths between

16-28 cm covers a broad area from Alberta to Indiana. The next zone covers a less defined area that includes Edmonton, Winnipeg, and St. Paul with depths of 29-42 cm. The final two zones are in the far north east corner of the study area. The shallower of the two has depths of 43-55 cm and contains five grid cells. The other, contains just three grid cells and has an annual max between 56 and 68 cm.

The average day of largest annual depths does not exhibit as well of a defined pattern as maximum snow depths (Figure 3.6b). The earliest maximum is reached between December 10th and December 26th in four cells in the south west corner of the study area. The next zone reaches a maximum between December 27th and January 10th with five cells spread out throughout the study area in no distinct pattern. The next zone covers a broad area between January 11th and January 26th that includes many of the cities in the southern half of the study area including Cheyenne, WY, Lincoln, NE, Des Moines, IW, Madison, WI, Topeka, KS, Jefferson City, MO, Springfield, IL, Indianapolis, IN, Oklahoma City, OK, Little Rock, AR, and Nashville, TN. North of this zone is another large zone with Bismarck, ND, Pierre, SD, and St. Paul, MN reaching maximums between January 27th and February 10th. Most cells in this zone stretch from Alberta to northern Wisconsin, but six cells are located further south. The final zone has a well-defined angled pattern with maximums, on average, between February 11th and February 26th. This zone also includes two grid cells in northern Wyoming. These northern cells reach their maximums as much as 78 days later than southern latitude maximums in December, likely due to northern cells accumulating depth throughout the year, reaching their maximum later in the season, while the southern latitudes in the study area tend to reach their maximum from singular storms.

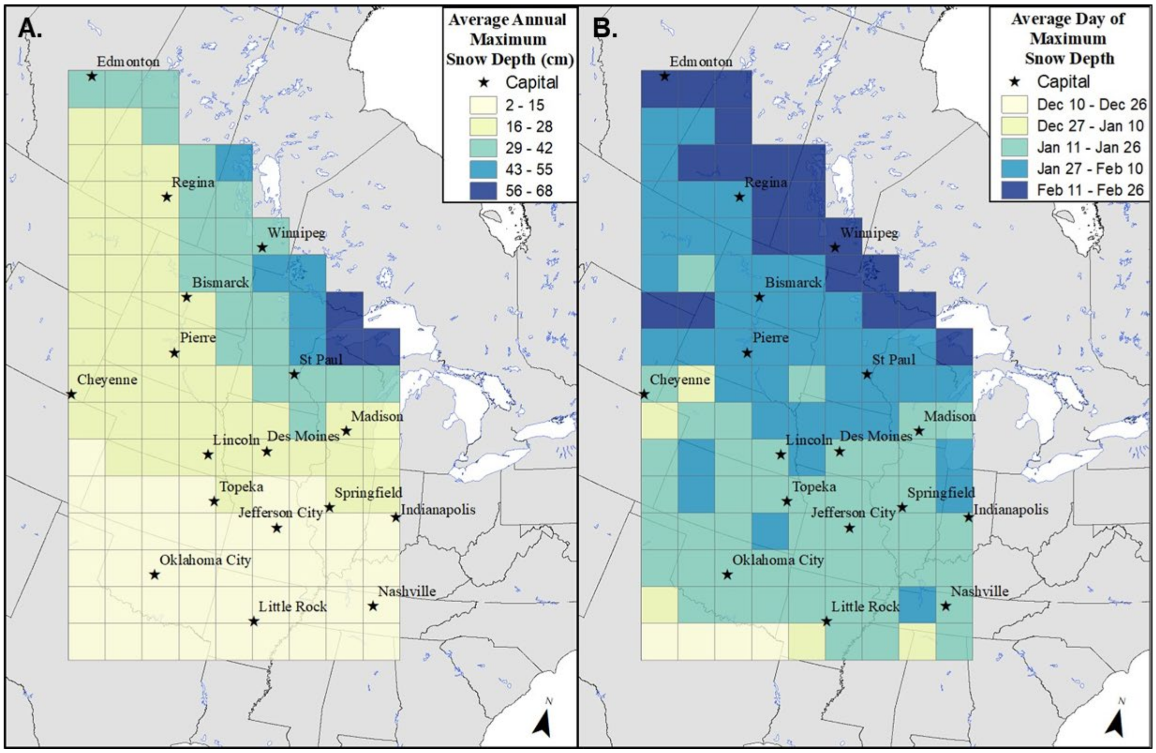

Figure 3.6. a) Average annual maximum snow depth for each study cell. b) Average day of maximum snow depth for each cell.

The maximum snow depth for the entire period (figure 3.7), reveals five general patterns of depth with more extreme maximums progressing north with three of the five being well defined spatially. The zone of shallowest depths is once again in the south with depths between 12-36 cm. This zone covers northern Texas to Kentucky with parts of Kansas and a cell in Nebraska included. The next zone has depths of 37-60 cm in a less clear, but still present, angled pattern. The final well-defined zone with maximum depths between 61-83 cm stretches into Saskatchewan, down to northern Illinois. Within this zone, greater depths are present with 13 cells spread throughout with 84-107 cm and four cells in the northeast corner of the study area having maximum depths of 108-131 cm.

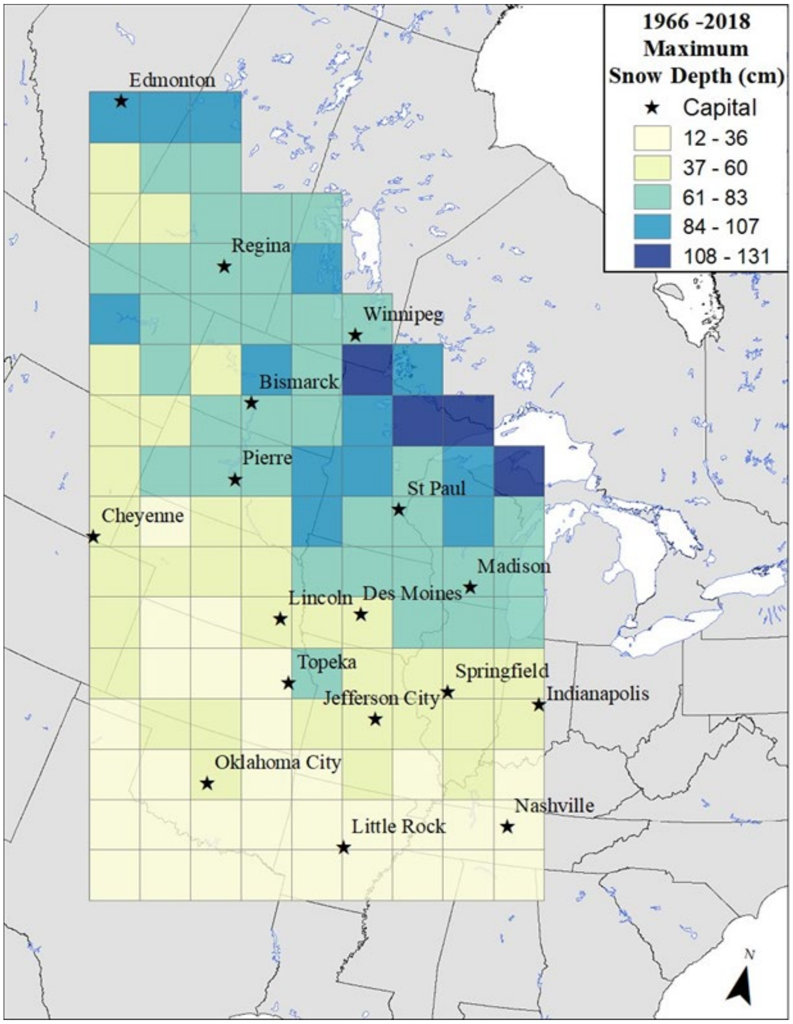

Figure 3.7. Extreme maximum snow depth for each cell at any time during the 52-year study period.

3.6 Summary

The key results of the region snow depth climatology include:

- Moving in a general northward manner, cells have increasing depth and the snow season lasts longer. Southern cells have occasional snow cover but spend a large majority of the winter snow free.

- Northern subregions accumulate snow depth throughout the year resulting in longer seasons as well as later maximum depths compared to southern subregions that experience early maximums and short snow seasons.
- Northern subregions 3 and 4 reach their “plateau” peak depths at generally the same time of year, despite the most northern subregion 4 depths being greater.

Chapter 4: Time Series Analysis of Snow Depth

4.1 Decadal Variability of Snow Depth Over the Winter Season

To explore potential variability and trends in snow depth, an anomaly analysis is undertaken. Results are displayed on a grid cell basis by decade in figure 4.1. This is done by taking the decadal average number of days where snow depths are greater than 7.6 cm. Once calculated, the decadal average is subtracted from the long-term average to get a decadal anomaly represented as a percentage difference from the full period average. The five snow season decades evaluated include 1968/69-1977/78, 1978/79-1987/88, 1988/89-1997/98, 1998/99-2007/08, and 2008/09-2017/18.

The largest positive anomaly is the decade ending in 1977/78 with just 14 cells showing a negative anomaly. Conversely, the largest negative anomaly appears in the decade ending in 2007/08. In this decade, 86% of the grid cells have a negative anomaly with 19% having a negative anomaly at least -10% below the long-term average. The largest decadal variability in snow depth found within the study region is within subregion 2, from Montana east to North Dakota. The other three decades do not have as distinct a pattern, but still exhibit variations. The decade ending in 1987/88 shows an area of large negative anomalies of less than -5%, north of Cheyenne, but also positive anomalies of greater than 0% in the south. The decade ending in 1997/98 shows slightly the opposite. In this decade, most negative anomalies are south of Cheyenne with a row of negative anomalies less than -5% west of Madison, WI. North of Cheyenne a pattern of negative anomalies is found in the west, with positive anomalies in the east and far north. The final decade 2017/18 shows a mix of negative and positive anomalies. The largest negative anomalies are in the North, around Edmonton, south of this there are large positive anomalies, greater than 5%. This pattern ends south of Cheyenne where the anomalies are only slight variations from the period average.

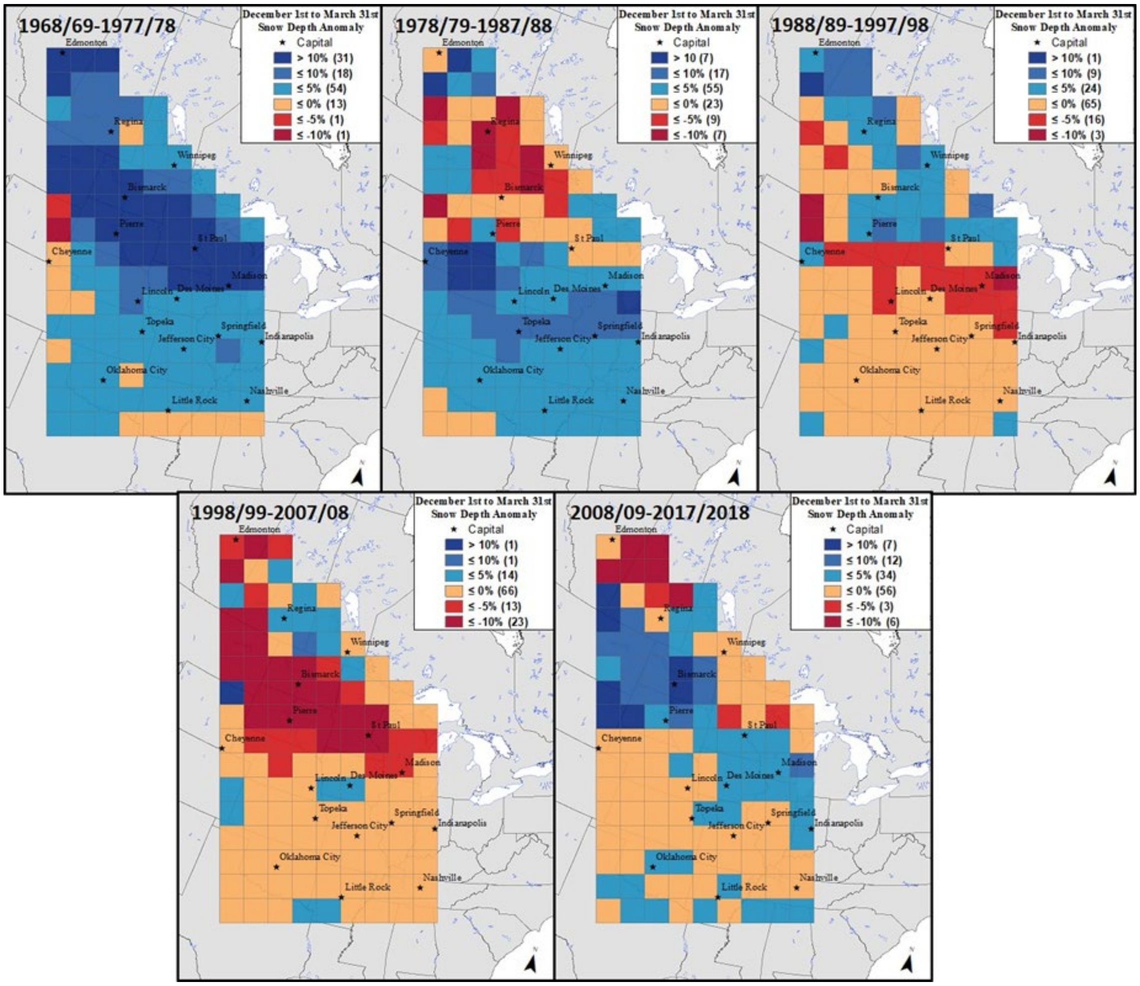

Figure 4.1. Decadal anomaly of the period average percentage of days above a threshold depth of 7.6 cm compared to the complete period average in figure 3.2. Parentheses indicate the number of occurrences within each classification.

4.2 Trends and Variability in Snow Depth and Extent

Comparing the rate of change of snow depth and extent will help answer the objective of whether snow depths are changing at different depths and whether snow depth is changing faster, slower, or at the same rate as snow extent. Using the four previously defined subregions, a time series analysis of the annual number of days above threshold depths of 2.54 cm, 7.6 cm, 15.2 cm, and 25.4 cm is undertaken. Following this analysis, the sum of snow depth and snow depth extent at the lowest threshold depth are calculated monthly, then averaged for all cells to generate the annual regional total.

4.2.1 Subregion 1

Subregion 1 has the shortest season and the least amount of snow. The variation in depths are presented in figure 4.2. Depths of 2.54 cm and 7.6 cm have decreased over the past 52 years, at a rate of -8% per decade at 7.6 cm and -6% at 2.54 cm, though neither depth change is significant at a P-value < 0.05. The two greater depths examined for the subregions were reached on several days in 1979, but overall occur rarely.

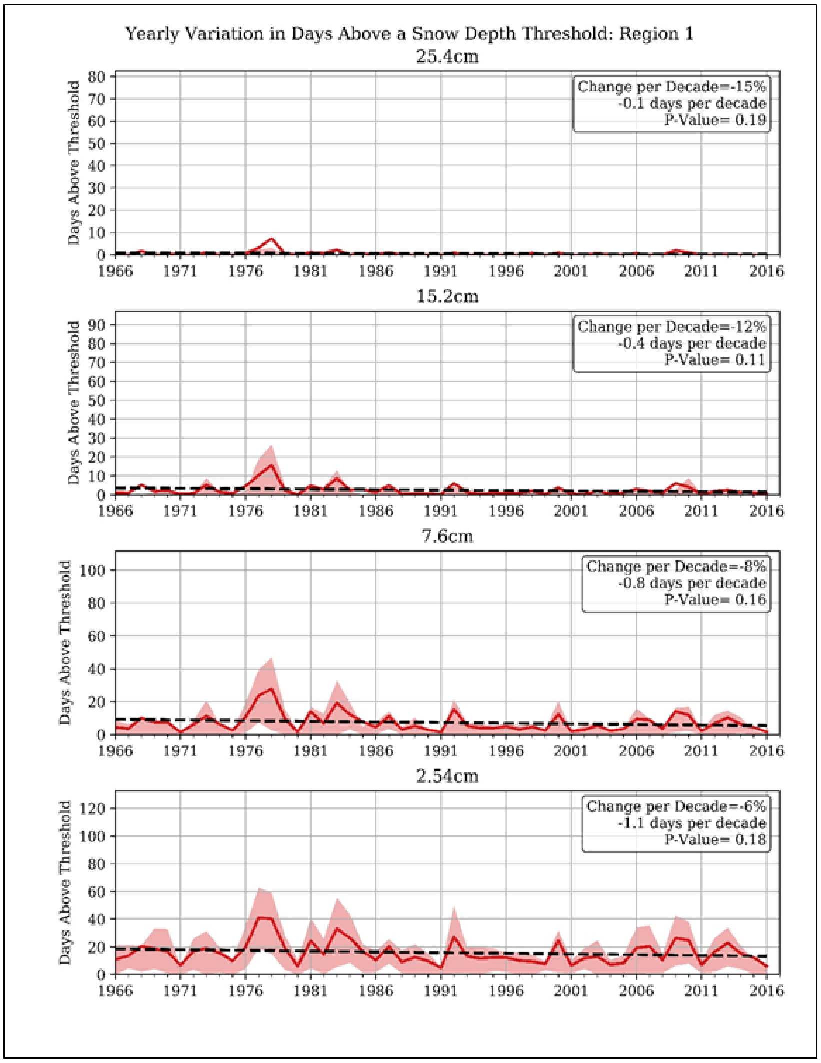

Figure 4.2. Days above various threshold depths from December through March for sub-region 1 from 1966-2018 The inset shows the percent change per decade, the change expressed as number of days per decade, and the P-value significance.

Time series of the annual snow season sum of days with at least 2.54 cm of snow on the ground and the average depth for each season are presented side by side in figure 4.3 for each month. Subregion 1 has the most days with coverage in January as well as the greatest snow depth. Within this subregion there is rarely measurable depth in April and November, with March accumulating roughly as much as November. The trends for this subregion are negative in nearly every month for both extent and depth with significant trends in November and January (*$P < 0.05$*). The only exception comes in

December snow extent where there is no trend.

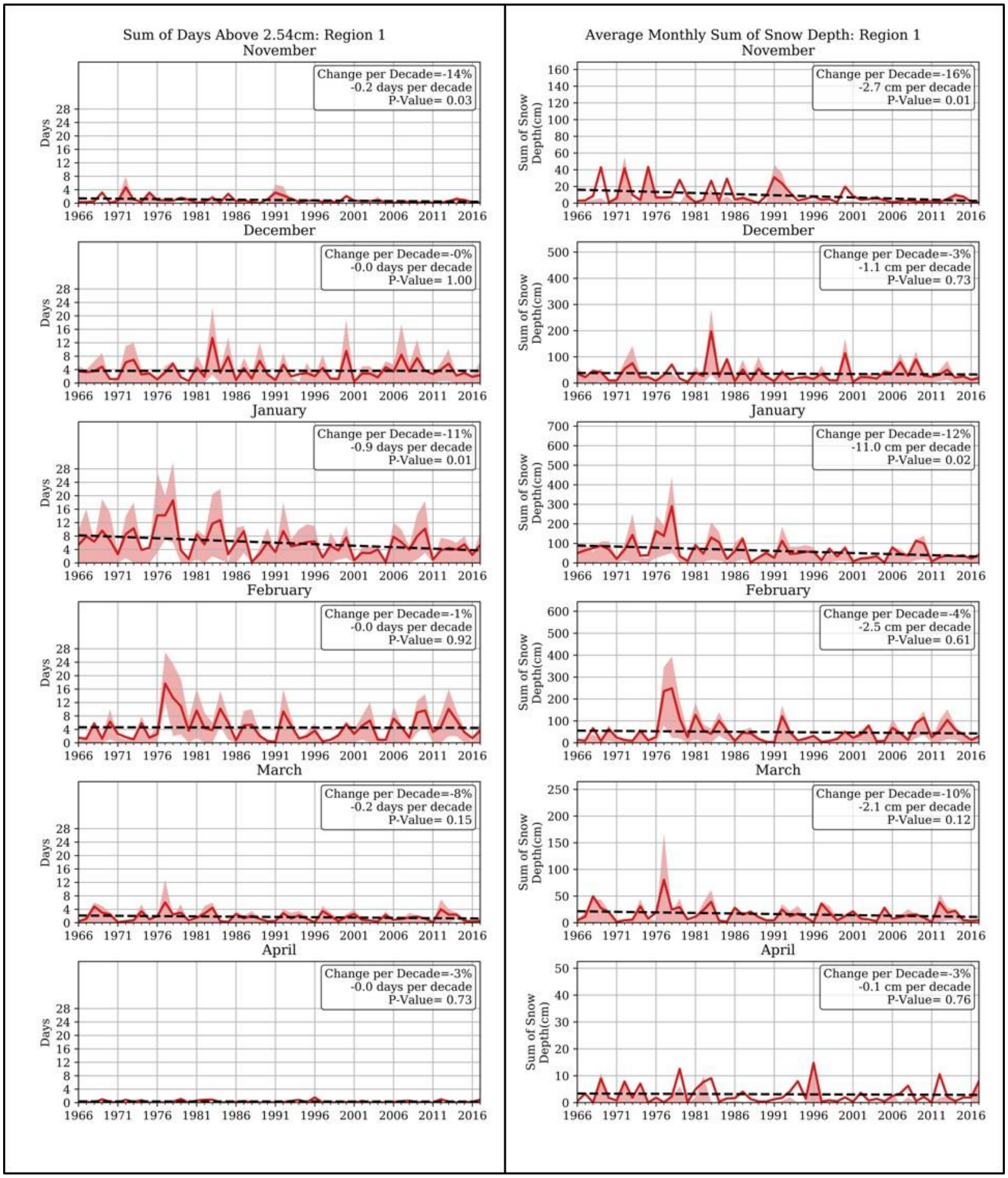

Figure 4.3. Days per month with average sub-region snow depth of at least 2.54cm (left) and sum of snow depth (right by month) for subregion 1 from 1966-2018. Averages are indicated by solid lines, with the 25th and 75th percentiles shaded. A linear regression for each plot is denoted by a dotted black line. The insert with each plot includes the percentage change per decade, the numeric change per decade, and the p-value significance of the trend line.

4.2.2 Subregion 2

Snow depths of 2.54 cm, 7.6 cm, and 15.2 cm are reached on a yearly basis in subregion 2, while 25.4 cm was only reached in a few years such as 1968, 1977, and 1978 among others. (figure 4.4). A downward trend in depth is noted at all levels, with the greatest decrease at 15.2 cm, though nothing is significant at $P < 0.05$.

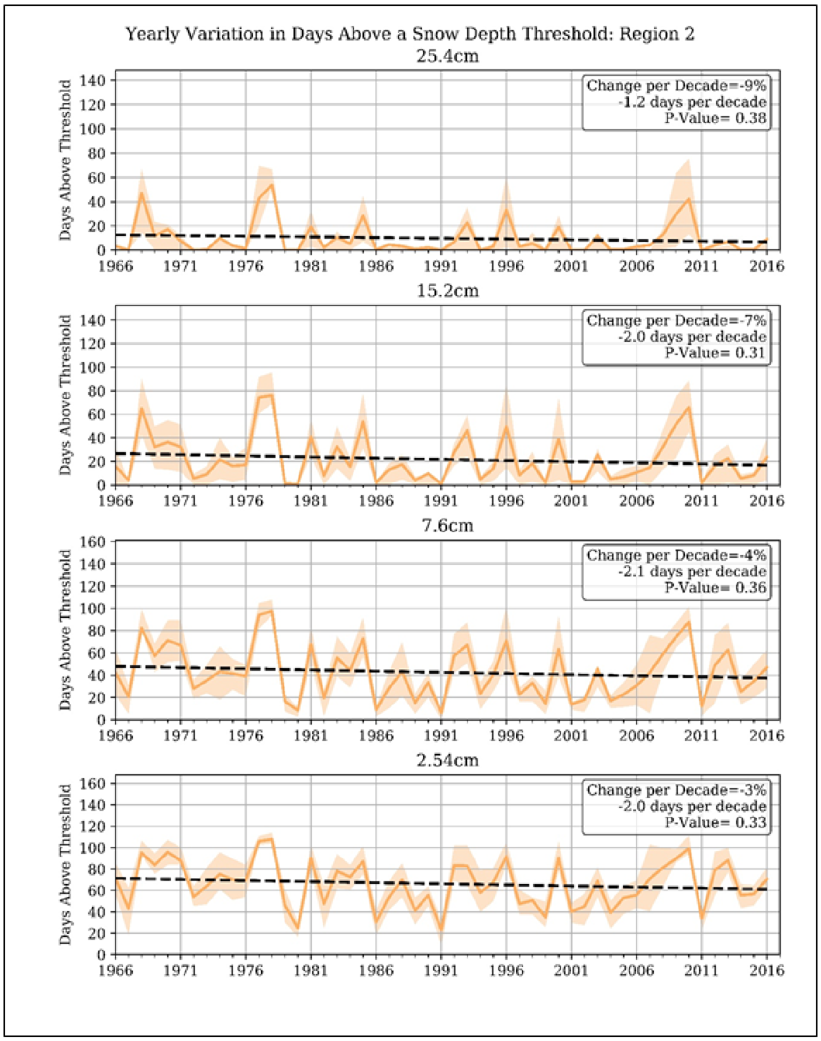

Figure 4.4. Same as figure 4.2 except for sub-region 2.

Monthly time-series show considerable variability in extent and depth (figure 4.5). The largest decrease in extent is seen in January at -3% per decade. This decrease is most notably seen in January and February with both months showing decreases of -7% per decade. The actual decrease is larger in January with a rate of -2.7 cm per decade compared to February with a decrease of -2.36 cm per decade. Neither extent nor depth trends were significant. Many months had wide swings in extent between years. For example, January displayed full coverage in some years, while others had as few as 6 days coverage. April extent and depth both increased over the study period, a rarity for this region, and as will be seen throughout this study. The increase was greater in extent than in depth, while for negative trends seen in other months and subregions, the decrease in the depth exceeds that of extent.

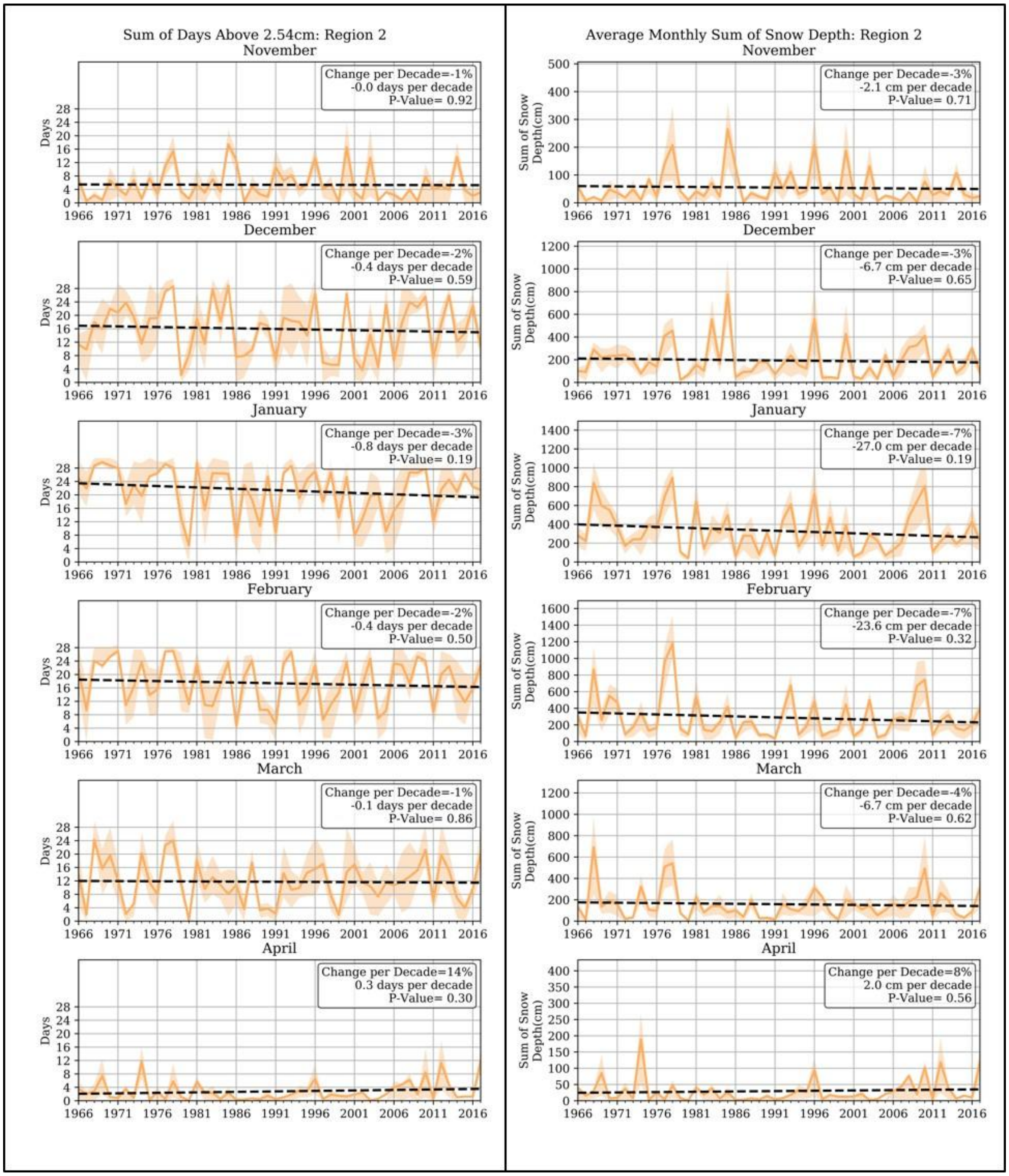

Figure 4.5. Same as figure 4.3 except for sub-region 2.

4.2.3 Subregion 3

As with the first two subregions, subregion 3 has experienced an annual decrease in all snow depths (figure 4.6). Again, the greatest percentage decrease is seen at the greatest depths. The most significant changes (*P < 0.05)* in this region are in the lowest snow depth of 2.54, but 7.6 cm experienced a moderately significant trend of *P* = 0.06. Both snow depths experienced an approximate 20-day decrease over the five-decade study period.

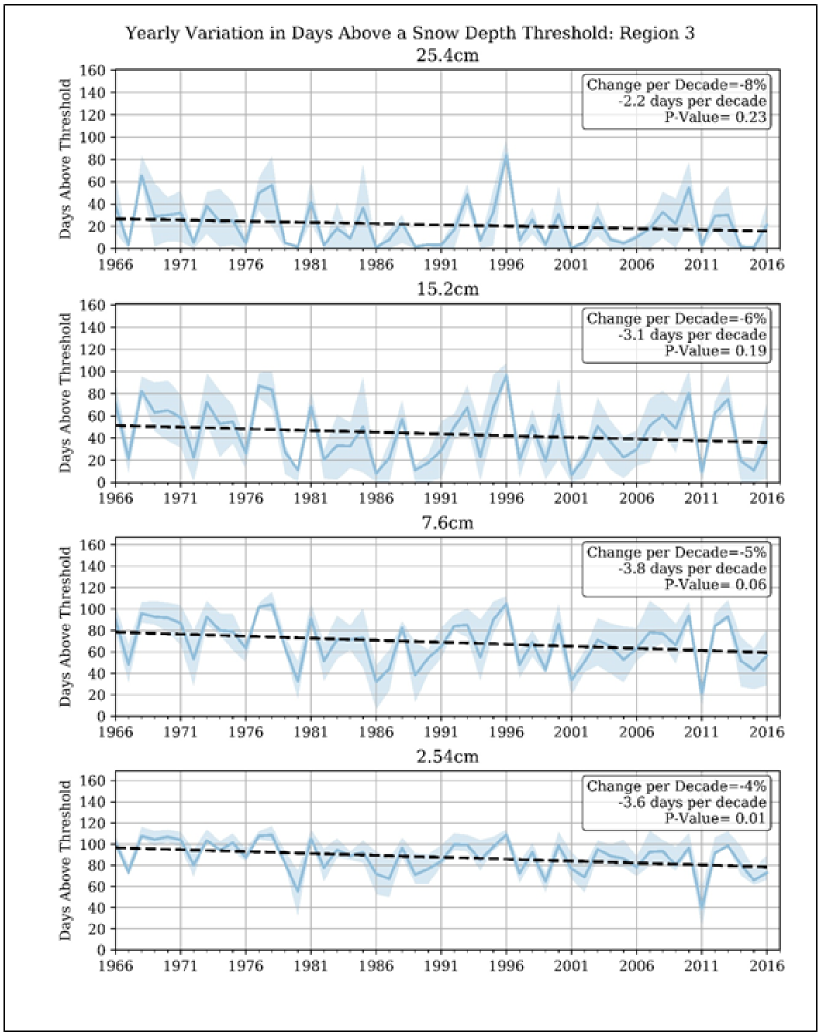

Figure 4.6. Same as figure 4.2 except for sub-region 3.

Like subregion 2, subregion 3, shows an increase in extent and depth in April (figure 4.7). While the percentage increase is less in April than in subregion 2, the actual days per decade increase is the same with 0.3 days per decade. This subregion also shows an increase in the month of November, although the increase is smaller. Once again, the months with the overall deepest snow depths are showing the greatest decrease in depth over time, most notably January and February. January exhibits the largest decrease in both extent and depth, with latter being greater. This region shows the largest decrease in extent compared to the others. January in this is decreasing by -1.3 days per decade (P = 0.01). While this is the largest decrease in days per decade, the percentage decrease is not as extreme as January in subregion 1.

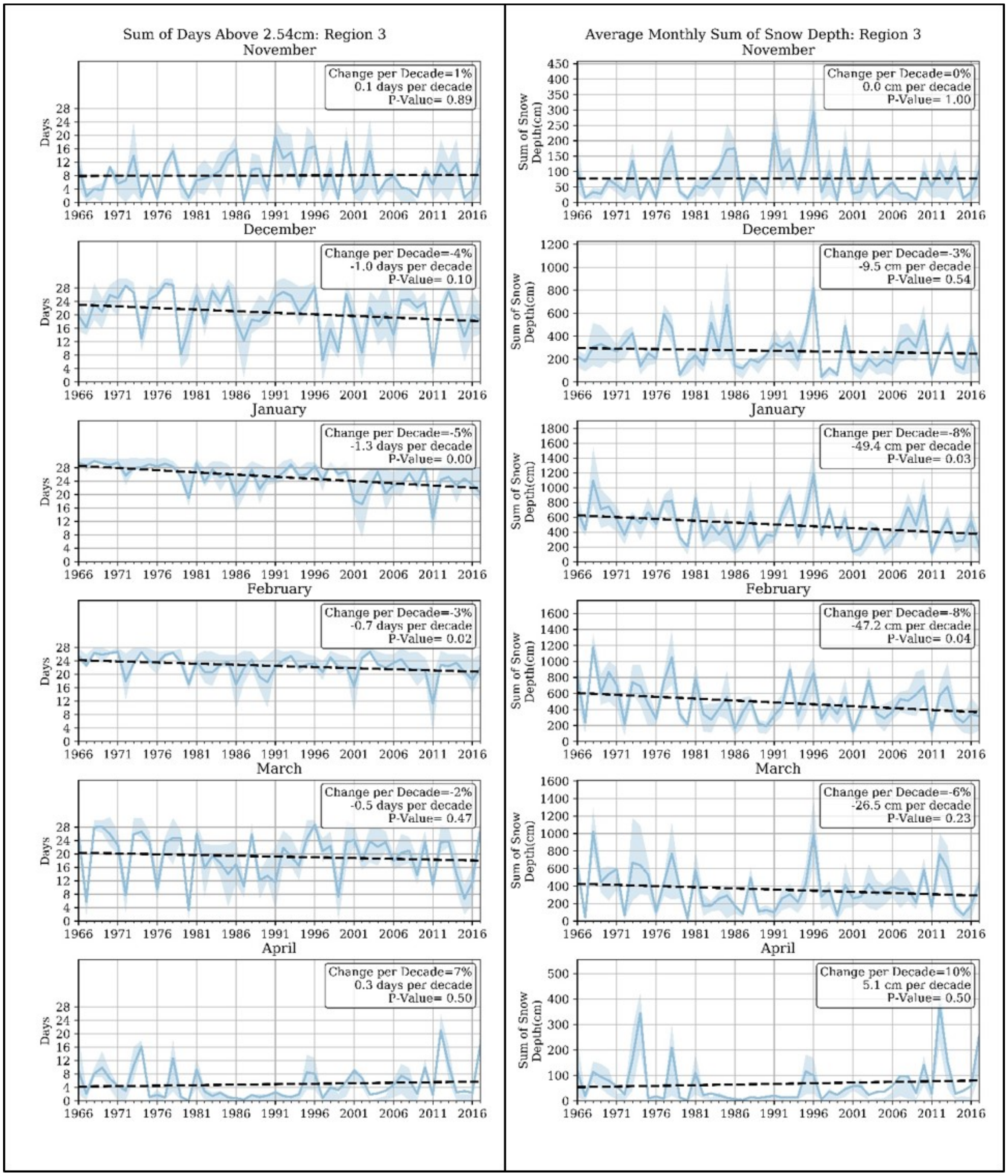

Figure 4.7. Same as figure 4.3 except for sub-region 3.

4.2.4 Subregion 4

As introduced earlier, subregion 4 receives the deepest snow and has the longest season. Annual trends at all four depths were significant at $P < 0.05$ (figure 4.8). The deeper depths exhibit the most year to year variability compared to lower depths, showing that depths of 25.4 cm or greater are not guaranteed every year.

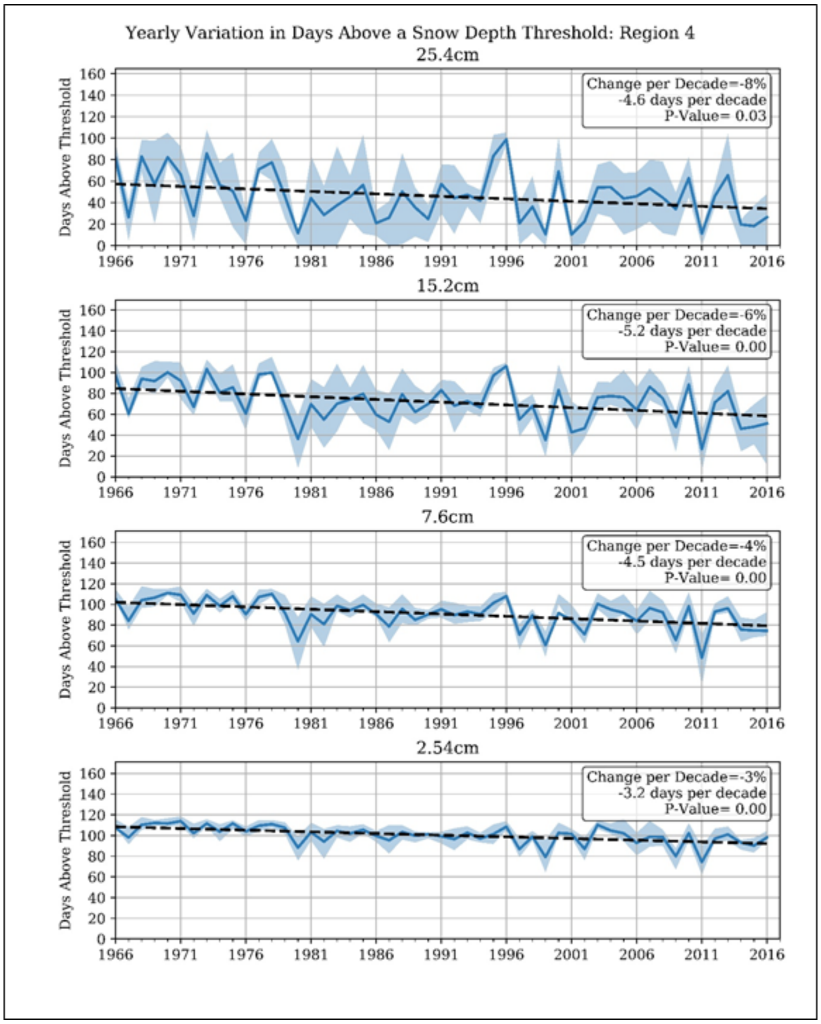

Figure 4.8. Same as figure 4.2 except for sub-region 4.

This subregion showed decreases in extent and depth in all study months (Figure 4.9). The largest decreases in depth are seen in January and February, each with a percentage decrease of -8%. February depth decrease of -7.78 cm per year. December and March also show substantial decreases in snow depth with March showing a decrease of -6.0 cm per year and December decreasing with -2.81 cm per year. Like depth, the extent has decreased in all six months as well. January, February, and March all show a decrease of -3% per decade which is a change of -0.8 days per decade in all months except

February which had a change of -0.7 days per decade. The trends in these months were all statistically significant (*P* < 0.05). The “shoulder months” of November and April shows a smaller change in extent throughout the 52-year period, changing by about 1% per decade compared to the sum of depth which is changing by -4% per decade with high variability in both months.

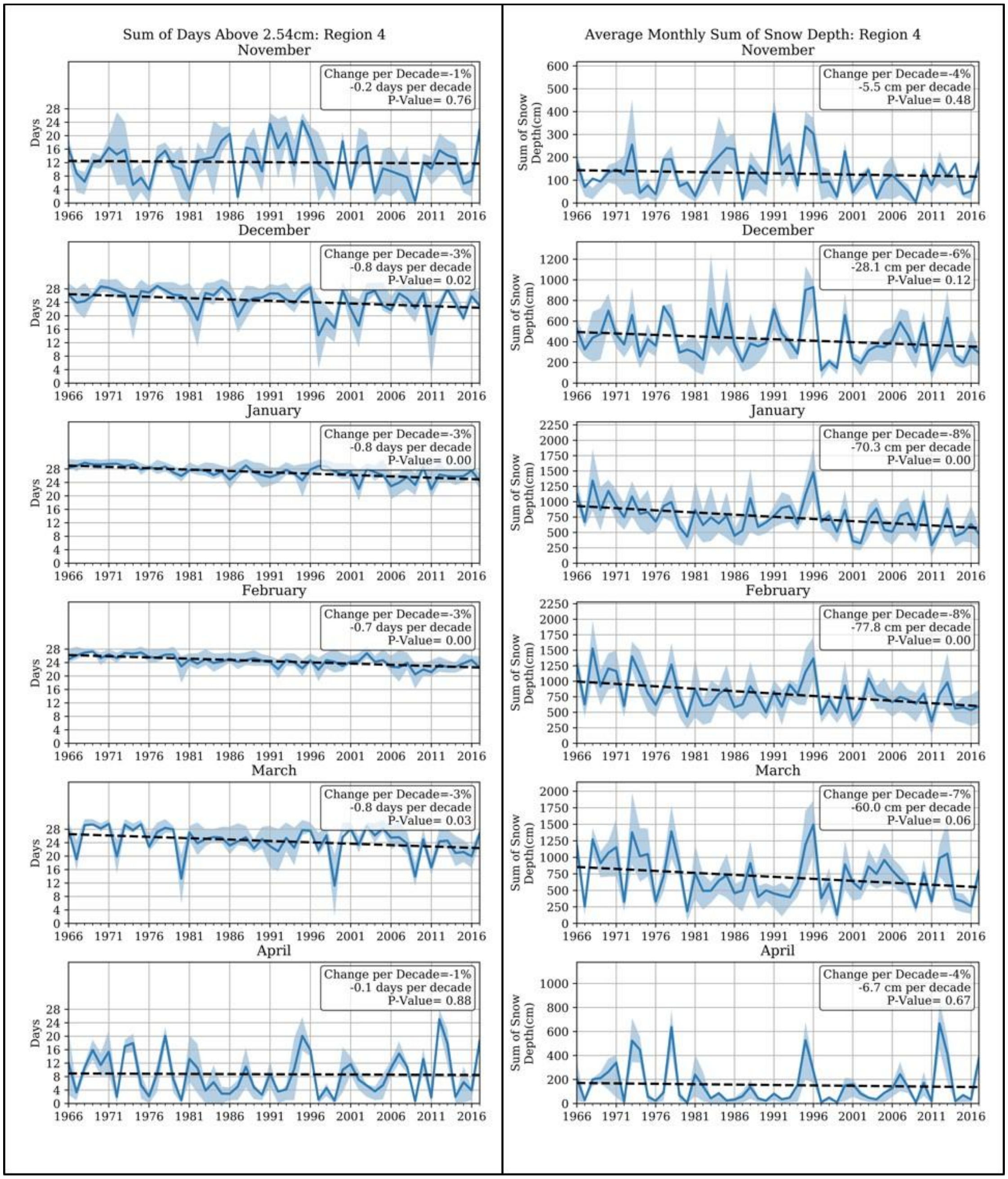

Figure 4.9. Same as figure 4.3 except for sub-region 4.

The results from the sub-regional analysis above are summarized in Table 2 which shows snow extent and snow depth side by side. This table includes the percentage change for the entire period and the significance of the analysis. The table shows that the most significant trends in snow depth were in January (subregion 1, 3, and 4) and February (subregion 3 and 4) all showing decreases. There are no significant increases in the sum of snow depths. Snow depth extent in December was significant for subregions 3 and 4 with decreases in both of -22% and -16%. In November, extent is significant ($P < 0.05$) for subregions 1, 3 and 4, with subregion 3 experiencing a slight increase of 4% while subregion 4 experienced a decrease of -7% and subregion 1 a decrease of -73%. April also showed a significant trend in snow depth extent for subregions 3 and 4. Once again, subregion 3 increased, this time of 36%, while subregion 4 had a decrease of -5%. This highlights the variability within the shoulder months when snow extent is at its lowest.

Month		Region1		Region 2		Region 3		Region 4	
		Snow Depth	Snow Depth Extent	Snow Depth	Snow Depth Extent	Snow Depth	Snow Depth Extent	Snow Depth	Snow Depth Extent
November	Percent Change (1966-2018)	-87% (0.3)	-73% (3%)	-18% (1.8)	-4% (19%)	0% (2.5)	4% (29%)	-20% (4.2)	-7% (44%)
	P-Value	0.01	0.01	0.71	0.19	1.00	0.00	0.48	0.00
December	Percent Change (1966-2018)	-15% (1.1)	0% (12%)	-17% (6.1)	-12% (54%)	-17% (8.6)	-22% (74%)	-30% (13.4)	-16% (90%)
	P-Value	0.73	0.92	0.65	0.5	0.54	0.02	0.12	0.00
January	Percent Change (1966-2018)	-64% (0.3)	-56% (20%)	-35% (10.5)	-18% (73%)	-41% (15.9)	-24% (92%)	-39% (23.8)	-14% (99%)
	P-Value	0.02	0.15	0.19	0.86	0.03	0.47	0.00	0.03
February	Percent Change (1966-2018)	-23% (1.7)	-4% (16%)	-35% (9.8)	-12% (65%)	-41% (16.4)	-14% (90%)	-41% (27.0)	-14% (99%)
	P-Value	0.61	0.73	0.32	0.3	0.04	0.5	0.00	0.88
March	Percent Change (1966-2018)	-50% (0.5)	-42% (6%)	-20% (5.0)	-4% (39%)	-32% (11.4)	-12% (68%)	-37% (22.2)	-16% (89%)
	P-Value	0.12	0.03	0.62	0.92	0.23	0.89	0.06	0.76
April	Percent Change (1966-2018)	-15% (0.1)	-17% (1%)	43% (1.0)	71% (10%)	50% (2.2)	36% (17%)	-20% (5.0)	-5% (31%)
	P-Value	0.76	1.0	0.56	0.59	0.50	0.01	0.67	0.02

Table 2: Snow depth extent is represented as the percentage of days covered by 2.54 cm *or more of depth. The monthly percent change in snow depth extent is shown here with the average monthly percentage cover displayed in the parentheses. The change in the sum of snow depth is displayed as a percentage with the average monthly snow depth displayed in the parentheses. Significant trends ($p < 0.05$) are highlighted in green. Positive trends are represented by shades of blue highlighting, negative trends are represented by shades of red highlighting. If there was no overall trend, there is no highlighting.*

4.6 Summary

The key results of the snow trend analysis over the 1967-2018 period include:

- Annual snow depths are decreasing in all subregions with significant decreasing trends in subregions 3 and 4. The largest decreases percentagewise are noted within greater depth categories for all subregions.
- December, January, February, and March show decreases in snow depth and extent across all subregions. November and April exhibit increases in snow depth in several subregions.
- All decreases in snow depth exceed those in extent. In the fewer cases of increases in these variables it is extent leading depth.

Chapter 5: Discussion and Conclusions

Snow extent and depth climatologies were generated for central North America using a gridded station-based dataset that underwent extensive quality control as part of this unique study.. Results show a pattern of increasing depths northward in a pattern angled from northwest to southeast. Southern cells experience little seasonal snow cover, with maximum depths achieved early in the season. Snow continues to accumulate in northern cells throughout the season, reaching their maximum in January and February. Evaluation of snow extent and depth over a 52-year period ending with the 2017/18 season reveals that snow depth and extent have been decreasing over most of the study region. Significant decreases have occurred in the months of January and February, particularly in the two most northern sub-regions These trends are more pronounced for depth than extent, particularly in the northern zones with climatologically greater depths than further south. Despite decreases in most of the study region in most months, there were some increases in depth and extent in November and April in central subregions 2 and 3.

Snow cover has societal interactions associated with drinking water, agriculture, and flood hazards. The Rocky Mountains in the west replenish many reservoirs that are used for drinking water. Within the study region, snow cover can melt and replenish ground water reservoirs that are used as sources of drinking water as well as irrigation. Irrigation is not the only use of snow cover for agriculture. While variable across the region, snow cover provides a useful means of storing water and slowly releasing melt into the soil throughout the winter in areas where the snowpack is ephemeral during the season and in northern regions releasing it during spring melt. This differs from rainfall which may at one time provide more water than the soil can absorb, thus damaging fields and introducing a flood threat. Another benefit of a snow cover is its insulative characteristic that can shield soils from freezing deeply and reduce potential damage to winter crops (e.g. wheat). This insulation effect also influences the local and regional surface energy balance by reducing energy transfers between the ground and atmosphere.

A concern about the timing of snowmelt, anywhere in the region, but particularly in northern portions where snow accumulates throughout the winter is rapid melt. Such concern is enhanced when rain accompanies the melt. With precipitation falling as rain this will saturate the soil further south and when inevitable snow melt flooding comes it will not be able to be absorbed by soil. This melting snow, with a combination of heavy rain, can cause historic, expensive flooding such as the events of 2019 in states along the Missouri River and the various spring floods of the Red River of the North. These flooding events reveal that even with decreasing trends, snow cover remains variable from year to year. Other factors such as abrupt temperature changes or heavy rain events could be associated with melt, but additional investigation of these events would be necessary.

The trends seen in this study are likely a result of other climatological variables that influence snow depth, one of which is snowfall. Snowfall is determined by the availability of moisture as well as temperatures below 0°C, placing the trends in snow depth in context of other climatological factors such as temperature, precipitation, or even atmospheric teleconnection patterns. Temperature has increased from November to April across the region during the study period. The largest increase in temperature has occurred in the Upper Midwest where temperatures are increasing at 0.7°F per decade (figure 5.1). An upward trend in precipitation in the Upper Midwest between 1966 to 2018 is at about 0.08 inches (0.2 cm) per decade. The Northern Rockies and Plains climate region has shown an increase of 0.6°F per decade, but precipitation has shown no positive or negative trend for the 52-year period. The South climate region has shown the smallest increase in temperature but has had the largest increase in precipitation.

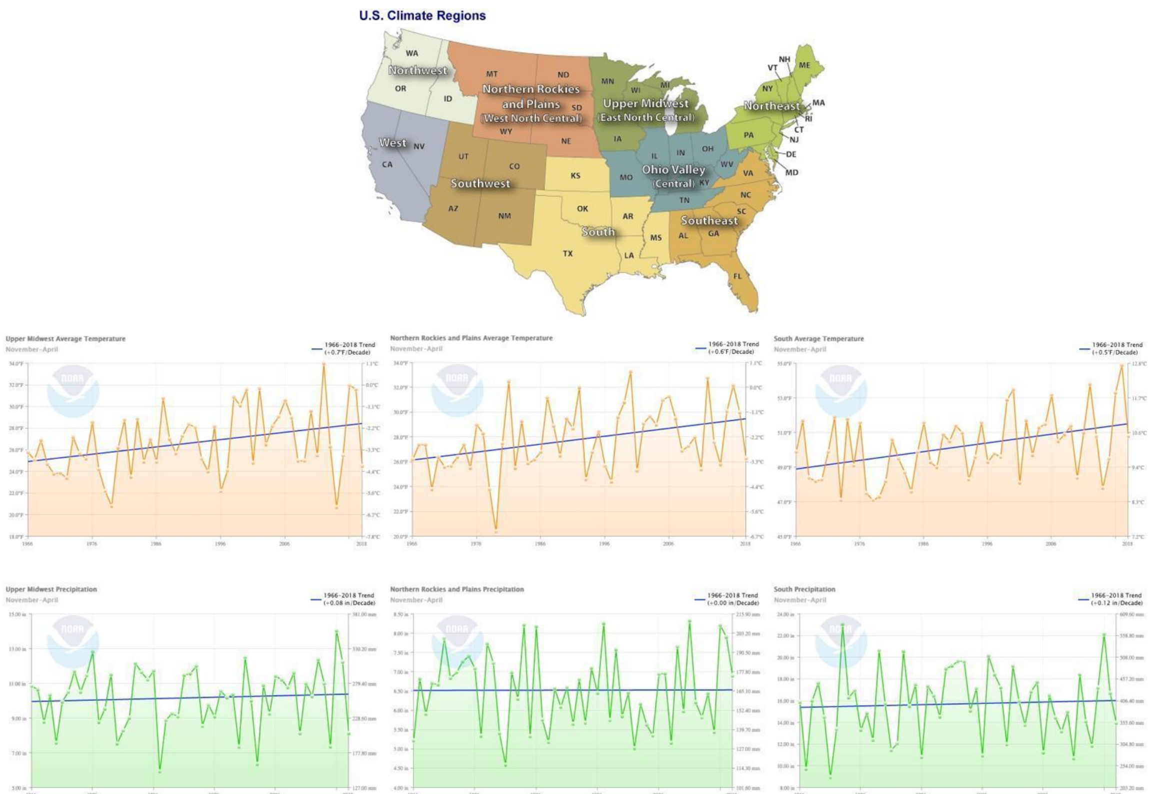

Figure 5.1 November through April temperature (top row) and precipitation (bottom row) trends from 1966-2018 courtesy of NCEI Climate at a Glance. Each regional division is shown in the map above the plots. The plots on the far left are for the Upper Midwest, the middle is the Northern Rockies and Plains, and the far right is the South Climate Region.

While the results of this study report that snow depth and snow extent were both decreasing during this period, these plots indicate that there has been a slight increase in the trend in precipitation. This means that there is possibly a shift in the precipitation regime in the region from snowfall to rain, possibly contributing to the decrease in snow depth, as well as extent. While snowfall was used as a supplement to this study, a detailed analysis was beyond its goal. Such an analysis in combination with temperature would provide more insight into the patterns that we see in the results of this study.

Trends in snow depth may also be linked to atmospheric teleconnection patterns that affect both precipitation and temperature. Wintertime precipitation in this region is a product of mid-latitude cyclones linked to large scale atmospheric patterns including El Nino-Southern Oscillation (ENSO) and the Pacific-North American (PNA) teleconnection that have regional implications as well as global effects of varying magnitudes. In central North America, the negative phase of the PNA tends to lead to more ridging of upper level pressure patterns resulting in warmer and drier conditions, resulting in less snowfall and less accumulation during the winter (Ballinger, 2018). ENSO, on the other hand, has varying effects across this study region. La Nina is known as the opposite phase of El Nino, in which fluctuations in the polar jet stream cause the northern half of North America to experience colder winter temperatures while the other half experiences warmer and drier conditions ("Climate.gov ENSO"). Studies could further investigate the linkage between the patterns seen in this study with different phases of the PNA and ENSO.

This study makes use of data dating back to 1966, but other studies may benefit from expanding this study further into the past, and to a larger area. Doing so may be difficult as station data availability is increasingly reduced earlier in the century. Additionally, a larger study region could present its own difficulties where observations may be impacted by vegetation and elevation changes. Efforts to compare the results of this study to model output or satellite data could provide a higher resolution perspective on snow cover during this period and provide insights into studies covering future years.

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