2023

An Analysis of the Effect of Temperature on Asphalt Paving in South Dakota

S M Rahat Rashedi

AN ANALYSIS OF THE EFFECT OF TEMPERATURE ON ASPHALT PAVING IN SOUTH DAKOTA

BY

S M RAHAT RASHEDI

A thesis submitted in partial fulfillment of the requirements for the

Master of Science

Major in Civil Engineering

South Dakota State University

2023

THESIS ACCEPTANCE PAGE
S M RAHAT RASHEDI

This thesis is approved as a creditable and independent investigation by a candidate for the master's degree and is acceptable for meeting the thesis requirements for this degree. Acceptance of this does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

Michael Pawlovich
Advisor Date

Nadim Wehbe
Department Head Date

Nicole Lounsbery, PhD
Director, Graduate School Date

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to my advisor and chair of my committee Dr. Michael Pawlovich for his patience, support, and motivation. His guidance helped me in all the time of research and writing of this thesis. I would also like to thank my thesis committee member Dr. Suzette Burckhard for her guidance and insightful comments, and my graduate faculty representative Dr. Christopher Saunders for his guidance and support.

In addition, I am also thankful to the Department of Civil & Environmental Engineering of South Dakota State University for providing resources and a convenient learning environment to pursue my graduate study. The findings presented in this thesis are upon work funded by the South Dakota Department of Transportation. I thank my fellow lab mates Akosua Ofosua Okyere-Addo and Prashanna Sapkota for being such a wonderful group of people, both in and out of the lab.

Finally, I'd like to mention my family, especially my parents, wife, and son. Their support always gave me the necessary motivation to move forward in this journey.

CONTENTS

ABBREVIATIONS

DOT	Department of Transportation
MA	Moving Average
NOAA	National Oceanic and Atmospheric Administration
TMAX	Maximum Temperature
TV	Threshold Violation
WPR	Weekly Progress Report

ABSTRACT

AN ANALYSIS OF THE EFFECT OF TEMPERATURE ON ASPHALT PAVING IN SOUTH DAKOTA

S M RAHAT RASHEDI

2023

Temperature is an important parameter to consider for asphalt paving since this work is generally susceptible to weather due to outdoor construction. The South Dakota Department of Transportation (SDDOT) developed working day weather charts in 1998 to address the expected adverse weather days. This thesis investigated the effect of temperature on adverse weather days for asphalt paving and compared them to the value reported in the 1998 SDDOT study. Moreover, the thesis also examined how closely the maximum temperature data from project sites' weekly progress reports (WPR) matched the data from the closest weather stations. When the maximum temperature (TMAX) of a day is below a certain threshold maximum temperature, that day is counted as a threshold violation (TV) day. The weather data was collected from the National Oceanic and Atmospheric Administration (NOAA) website, and the WPR data of project sites was obtained from SDDOT. Average and 7-year moving average are used to analyze the TV days. The results show that the threshold violation days are generally greater than the State average adverse weather days at 45°F threshold both annually and monthly (January, April, October). However, these violation days are generally less than the State average when the threshold is 40°F. The lift thickness of surface course must be greater than 1 inch, when the temperature during asphalt paving is between 40°F and 45°F in order to get more working days. Most of the project sites (6 out of 9) show a low

percentage of maximum temperature data match with the corresponding NOAA stations. It is apparent from the analysis that that there is no direct relationship between the data match percentage, and the distance of project site and NOAA station.

CHAPTER 1: INTRODUCTION

1.1. Background

Transportation projects are generally more susceptible to weather conditions because they are constructed outdoors (Apipattanavis et al., 2010; Ballesteros-Perez et al., 2016; Chan et al., 2008; Herbsman et al., 1995; Ibbs et al., 2018; Moselhi et al., 1997; Russo, 1966; Schuldt et al., 2021; Senouci et al., 2016). Different types of construction projects (grading, paving, structural) are affected in various ways across the different climate regions of South Dakota (Kenner et al., 1998). Adverse weather is a primary factor causing delays and cost overruns on construction projects, which rely on labor and outdoor activities (Apipattanavis et al., 2010; Ibbs et al., 2018; Ibbs et al., 2017; Moselhi et al., 1997; Moselhi et al., 2002; Schuldt et al., 2021; Semple et al., 1994; Senouci et al., 2016). An adverse weather day refers to a day when the magnitude of a weather parameter (precipitation or temperature) is such that it creates conditions that inhibit the ability of the contractor to work (Kenner et al., 1998). The most significant highway construction operations affected by weather are earthwork, paving, and structural work (Apipattanavis et al., 2010). Precipitation, high or low temperatures, humidity, wind velocity, solar radiation are some of the major weather parameters that can have potential negative impact on road construction projects. Temperature can impact temperature sensitive works such as placing asphalt and curing concrete (Ibbs et al., 2018). The potential negative impact of temperature on asphalt paving works is analyzed for this thesis.

For South Dakota, the Standard Specifications for Roads and Bridges (South Dakota DOT, 2015) have set minimum temperature and seasonal limitations for surfacing

works. The minimum temperature is set at 45°F for a 1 inch or less compacted thickness of surface course (South Dakota DOT, 2015). The minimum temperature is reduced to 40°F for a compacted thickness over 1 inch (South Dakota DOT, 2015). The seasonal limitation is from May 1 to October 15 (inclusive) in both cases (South Dakota DOT, 2015).

South Dakota Department of Transportation developed Working Day Weather Charts for Transportation Construction 25 years ago (Kenner et al., 1998). One of the objectives of the study was to use the estimated number of monthly expected adverse weather days to develop working-day weather zones, maps, and charts for different types of construction projects (grading, surfacing, and structural) (Kenner et al., 1998). If the actual adverse weather days exceeds the expected number of adverse weather days over the life of a project, time extensions are warranted (Kenner et al., 1998). Since the study was done 25 years ago, advances in construction practices and potential climatic changes have occurred. So, the threshold for temperature, expected number of adverse weather days etc. may have changed over time. Thirty years is the standard adopted by the World Meteorological Organization for analyzing climatic patterns (Ballesteros-Perez et al., 2016). For this study, the 30-years (1991-2020) maximum temperature data is analyzed.

1.2. Objectives

The purpose of the thesis is to find the effect of temperature on asphalt paving works in South Dakota by analyzing the temperature data both annually and monthly. The specific objectives are listed below:

(i) To determine if the number of adverse weather days increased in the last 30 years (1991-2020) compared to the value reported in the 1998 SDDOT study.

(ii) To determine if the maximum temperature data of the closest weather stations match the weekly progress report (WPR) data for a subset of project sites.

1.3. Literature Review

The construction industry has evolved into a dynamic, high-risk business with accompanying growth in disputes and litigation (Ibbs et al., 2018; Kartam, 1999; Levin, 1998; Semple et al., 1994). Highway construction project duration is more critical today than in the past (FHWA, 2002; Gondy et al., 2007; Herbsman et al., 1995), partially due to proximity of workers to traffic. With the increasing number of resurfacing, restoration, and rehabilitation projects, often constructed under traffic, exposure of construction workers and motorists to harm is heightened (FHWA, 2002). Thus, proper selection of contract time improves safety and optimizes construction engineering costs. However, delays occur and normal, expected delays should be accounted for during determination of contract time.

Construction delays are usually measured as the number of days a significant milestone or completion date occurs beyond the forecasted date (Anastasopoulos et al., 2012; Kartam, 1999; Levin, 1998). Various weather conditions, including precipitation, temperature (high or low), humidity, and high wind can decrease productivity, waste resources, delay projects, and cause financial loss (Ballesteros-Perez et al., 2016; Ibbs et al., 2018; Ibbs et al., 2017; Koehn et al., 1985; Nguyen et al., 2010; Schuldt et al., 2021; Thomas et al., 2009; Thorpe et al., 2008). Quantifying the potential impact of weather is critical for the preparation of realistic and reliable schedules, cost estimates, and bids

(Ballesteros-Perez et al., 2016; Connors, 2003; Ibbs et al., 2018; Moselhi et al., 1997; Schuldt et al., 2021; Shahin et al., 2011).

Transportation projects are particularly susceptible to weather conditions (e.g., precipitation, temperature, wind), particularly earthwork, paving, and structural work (Apipattanavis et al., 2010; Ballesteros-Perez et al., 2016; Chan et al., 2008; Herbsman et al., 1995; Ibbs et al., 2018; Moselhi et al., 1997; Russo, 1966; Schuldt et al., 2021; Senouci et al., 2016). 45% of all construction activities are affected to some degree by weather (NCHRP, 1978; NCHRP, 1981). Moreover, 31 to 55% of all highway projects experience an average time delay of 44% in excess of their original contract periods (Anastasopoulos et al., 2012). Delays in the completion of highway construction and maintenance projects are important concerns to state highway agencies and contractors because delays can have several adverse consequences, such as extending the duration of active work zones, contributing to road-user dissatisfaction, and increasing the risk of litigation (Anastasopoulos et al., 2012).

Related to the thesis topic, temperature has a large impact on transportation construction projects. For example, low temperature severely impacts asphalt paving (Apipattanavis et al., 2010). Moreover, when the low temperature combines with precipitation and/or winds, the impact becomes more severe (Apipattanavis et al., 2010).

Beyond that, temperature impacts productivity of workers both physiologically and psychologically (Ibbs et al., 2017; Koehn et al., 1985; Levin, 1998; Moselhi et al., 1997; Schuldt et al., 2021). Extremely high temperature can reduce productivity from 10% to 30% (NCHRP 1978). When the temperature rises above 100°F, workers show signs of belligerence and irritability, and the quality of workmanship

deteriorates considerably (Levin, 1998). Figure 1 shows the potential health and mental performance issues due to high temperatures. If the temperature is above 110° F, work must stop to protect the workers (Nguyen et al., 2010; Schuldt et al., 2021; Thomas et al., 2009).

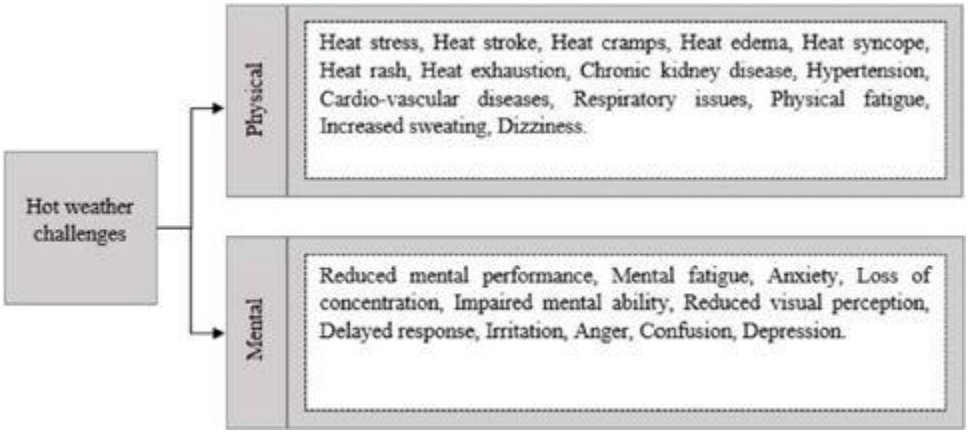


Figure 1. Health impacts of high temperatures (Karthick et al., 2023).

Extreme cold weather can significantly impact construction workers' health and productivity and task feasibility for outdoor work from 90% at 40°F to a 10% to 20% at −40°F (Anastasopoulos et al., 2012; NCHRP, 1978). Even less severe cold temperatures impact efficiency being as low as 50% at 20°F (Schuldt et al., 2021; Thomas et al., 2009). Exposure to cold temperatures affects the skin, muscles, and internal organs (Schuldt et al., 2021). However, the adverse labor productivity effects caused by cold temperatures can be reduced by wearing appropriate clothing (Schuldt et al., 2021). Temporary shelters and heaters can also be used to provide a warm-up space for workers, but care must be taken to ensure adequate ventilation is supplied (Koehn et al., 1985).

Contract time is the maximum allowed time in the contract for completion of all work (AIA, 2007; FHWA, 2002; Gondy et al., 2007; Herbsman et al., 1995; Jeong et

al., 2020; Michigan DOT, 2002; Okere, 2019). Transportation agencies often base contract time on construction season limits, quantity or production rates, work-flow techniques, estimated costs, and external factors such as utilities, railroads, and industrial access (FHWA, 2002; Gondy et al., 2007; Michigan DOT, 2002; NCHRP, 1981). Weather can produce project duration deviations of approximately 10 percent, and as project duration increases in length, seasonal weather changes become more difficult to avoid (Schuldt et al., 2021). So, the delays caused by adverse weather should be included in the project schedule.

Seven factors that lead to inconsistencies in the analysis of adverse weather for time extensions include: the definition of normal and abnormal weather, establishment of weather thresholds, impact of type of work, determination of lingering days, criteria for lost days, lost days equivalency to lost productivity, and workdays lost versus calendar days lost (Ibbs et al., 2018). Establishing definition and stipulation of inclement weather that can adversely affect construction works is important, along with quantitative threshold values for precipitation (in/hr), temperature (°F), humidity (%), and wind speed (mph) (Ibbs et al., 2018).

Related to the asphalt paving directly, the Standard Specifications for Roads and Bridges (Spec Book) for the State of South Dakota and bordering States (North Dakota, Wyoming, Iowa, Minnesota, Montana, Nebraska) were reviewed to find out the minimum temperature and/or seasonal limitations for asphalt paving works. The Spec Books for South Dakota, North Dakota, and Wyoming state that asphalt concrete should not be placed when the underlying surface is wet / frozen / damp (North Dakota DOT, 2022; South Dakota DOT, 2015; Wyoming DOT, 2015). Moreover, the Spec Books also stated

that asphalt concrete should not be placed when weather conditions prevent proper handling, compaction, or finishing (North Dakota DOT, 2022; South Dakota DOT, 2015; Wyoming DOT, 2015).

The Spec Books for South Dakota and bordering States have also stated numerical values related to minimum temperatures and seasonal limits for asphalt paving. Table 1 shows minimum air temperatures and seasonal limitations for surface course, subsurface course and shoulder course based on compacted thickness for South Dakota (South Dakota DOT, 2015).

Table 1. Minimum air temperatures and seasonal limitations (South Dakota DOT, 2015).

Compacted Thickness	Surface Course		Subsurface Course & Shoulder Course	
	Minimum Temperature	Seasonal Limits	Minimum Temperature	Seasonal Limits
1 inch or less	45°F	May 1 to Oct. 15 (inclusive)	45°F	None
Over 1 inch	40°F	May 1 to Oct. 15 (inclusive)	40°F	None

According to North Dakota Spec Book (North Dakota DOT, 2022), standard paving temperature for surface course is given in Table 2:

Table 2. Standard paving temperature (North Dakota DOT, 2022).

Compacted Thickness	Air Temperature for Surface Course
1-1/2 inches or less	45°F
More than 1-1/2 inches	40°F

According to Wyoming Spec Book (Wyoming DOT, 2015), the plant mix asphalt can be placed when the base temperature, surface temperature, or air temperature are at or above the requirements specified in Table 3:

Table 3. Air temperature limitations (Wyoming DOT, 2015).

Compacted thickness of Surface Course being Placed	Air Temperature
Compacted thickness < 1 in [25 mm]	60°F [15°C]
1 in [25 mm] < Compacted thickness < 2 in [50 mm]	50°F [10°C]
Compacted thickness ≥ 2 in [50 mm]	40°F [4°C]

According to Iowa Spec Book (Iowa DOT, 2015), HMA mixtures should not be placed under the following circumstances:

1) On a wet or damp surface

2) When road surface temperature is less than that shown in Table 4.

Table 4. Surface course lifts of asphalt mixtures (Iowa DOT, 2015).

Nominal Thickness - inches	Road Surface Temperature for HMA, °F
1	50
1 ½	45
2 and greater	40

According to the Minnesota Spec Book (Minnesota DOT, 2020), the pavement surface temperature and ambient air temperature shall be at least 50°F for asphalt paving. A damp pavement surface is acceptable, if it is free of standing water and favorable weather conditions are expected.

According to the Montana Spec Book (Montana DOT, 2020), bituminous material can only be applied with the Project Manager's approval, and when the surface temperature is at or above 60°F (16°C).

According to the Nebraska Spec Book (Nebraska DOT, 2017), Table 5 shall be used when there is a need to restrict the routine placement of asphaltic concrete as a result of cold temperatures.

Table 5. Cold weather asphaltic concrete placement (Nebraska DOT, 2017).

Lift Thickness	Minimum Surface Temperature
Less than 2 inches (50 mm)	45°F (7°C)
2 to 3 inches (50 mm to 75 mm)	37°F (3°C)
Greater than 3 inches (75 mm)	35°F (2°C)

The Standard Specifications for Roads and Bridges (Spec Book) for South Dakota and bordering States provide the information of the minimum temperature and/or seasonal limitations for asphalt paving works. It would help to set the threshold values for minimum temperature of asphalt paving works and analyze the adverse weather days from 1991 to 2020. Then the number of adverse weather days can be compared to the value reported in the 1998 SD DOT study (Kenner et al., 1998) for both annually and monthly.

CHAPTER 2: METHODOLOGY

To accomplish the objectives, two types of data were considered, Weekly Progress Report (WPR) and National Oceanic and Atmospheric Administration (NOAA). The WPR data was obtained from the South Dakota Department of Transportation (SDDOT). The provided WPR data represented sites that the SDDOT considered to be impacted by adverse weather over the past several years. The NOAA data is collected from the NOAA website (National Oceanic and Atmospheric Administration, 2022) by searching the NOAA records. The NOAA data that were obtained covered the State of South Dakota then subset to sites with nearly 30 years of data near the obtained WPR data. Brief descriptions of each of these data types are as follows:

2.1. Weekly Progress Report (WPR)

The weekly progress reports are published in the form of successive biweekly reports that come in a pdf format. In this report, all tables are not in Excel format. For this reason, it is required to copy and paste them individually into the required format to make them workable. The report contains the following data: “Days”, “Dates”, “Substantial Completion days”, “Field Work Completion”, “Weather and Comments”, “Type of Work” and “County”.

The “Weather and Comments” column basically contains the weather data. It has information about the sky condition (clear / sunny / cloudy / partly cloudy) precipitation (rain and snow), maximum temperature, minimum temperature, maximum wind speed, minimum wind speed, and some other comments like ‘No Work’, ‘Cool’, ‘Humid’, ‘Fog’ etc. Since this thesis is only focused on the effect of temperature on asphalt paving, the maximum temperature data is used for the analysis.

Based on the Weekly Progress Reports collected from SD DOT, the project sites are selected in such a manner that they spatially cover all parts of South Dakota. Table 6 shows the information related to the project sites such as location, project control number (PCN), type of work, and project duration. Most of the projects include road surfacing / resurfacing works. The projects in Charles Mix, Beadle, Walworth, and Butte are done in the most recent years (2019-2020). The other projects are also done in the latest years with the earliest in the 2006 to 2008 at Spink.

Table 6: WPR project sites with location and duration.

Sl.	Project Location		PCN	Type of Work	WPR Data Coverage
	County	in SD			
1	Hughes	Central	03WN	Replace Structure (1686' Steel Girder), Grading, PCC Pavement, Storm Sewer, Sanitary Sewer, Lighting, Signals, Plaza Park	10/25/2020 to 12/31/2020
2	Charles Mix	South	04HN	Grading, Shoulder Widening, Structure (RCBC), Asphalt Concrete Surfacing, & Lighting	04/05/2020 to 12/12/2020
3	Spink	North-East	4168(2007)	Grading, Str.s & Interim Surfacing (130' Prestressed Girder Bridge, 11'x'4 RC CIP BC, BC Options)	10/15/2006 to 06/20/2008
4	Beadle	South-East	04FH	Structure (290'-6 1/2" Prestressed Girder Bridge) and Approach Grading	06/09/2019 to 12/31/2020
5	Brown	North-East	02R3	Grading, PCC Surfacing, Lighting, Drainage Improvements, & Joint & Spall Repair	05/19/2013 to 10/20/2014
6	Minnehaha	East	03RT	Grading, Structures, PCC Surfacing, Lighting & Utilities	02/14/2016 to 08/01/2017
7	Walworth	North	03T1	Cold Milling Asphalt Concrete, Asphalt Concrete Resurfacing & Pipe Work	05/05/2019 to 11/16/2019

Sl.	Project Location		PCN	Type of Work	WPR Data Coverage
	County	in SD			
8	Butte	West	04G3	Polymer Chip Seal, Joints, Deck Overlay, Replace Bridge Rail, Approach Pavement	03/31/2019 to 08/29/2020
9	Custer	South-West	00LD	Cold Milling Asphalt Concrete, Asphalt Concrete Resurfacing, Epoxy Chip Seals, Remove Structure, Berm Repair and Drainage Imp	03/23/2014 to 09/30/2015
10	Perkins	North-West	4460	Grading, Structures & Interim Surfacing	03/30/2008 to 07/04/2009

The project site at Pierre in Hughes County is omitted from the WPR analysis since it has only 68 days (2 months 7 days) of data. Moreover, the working period is mostly in November and December when it is unlikely to perform the road surfacing works.

2.2. National Oceanic and Atmospheric Administration (NOAA) Data

As mentioned earlier, the NOAA data is collected from the NOAA website. The type of weather observation dataset is selected as ‘Daily Summaries’. The data is collected for the recent 30 years (1991-2020).

The NOAA stations were selected based on two criteria: (i) greater than or equal to 70% data coverage (ii) data were fully/partially available within 30 years period (from 01/01/1991 to 12/31/2020). Coverage is an approximation of total completeness based on the most complete data element, and the overall data range (National Oceanic and Atmospheric Administration, 2022). Based on these two criteria, the weather data of 433 NOAA stations were downloaded in 18 Excel files and then combined.

For the analysis of this thesis, the NOAA stations are selected based on the following criteria: (i) The NOAA station must be in the same county of the WPR project sites as mentioned in Table 6, and (ii) If there are multiple NOAA stations in one county having WPR project site, then the NOAA station must have the following criteria in hierarchical order:

(a) Having 30 years (1991-2020) data

(b) Having the highest data coverage.

For example, there are 2 NOAA stations in Belle Fourche of Butte County. The stations are BELLE FOURCHE 22 NNW, SD US (USC00390565) and BELLE FOURCHE, SD US (USC00390559). Both stations have 30 years (1991-2020) data. But their data coverage is 86.9% and 90.3% respectively. That is why the BELLE FOURCHE, SD US (USC00390559) station with the higher coverage (90.3%) was selected for the analysis.

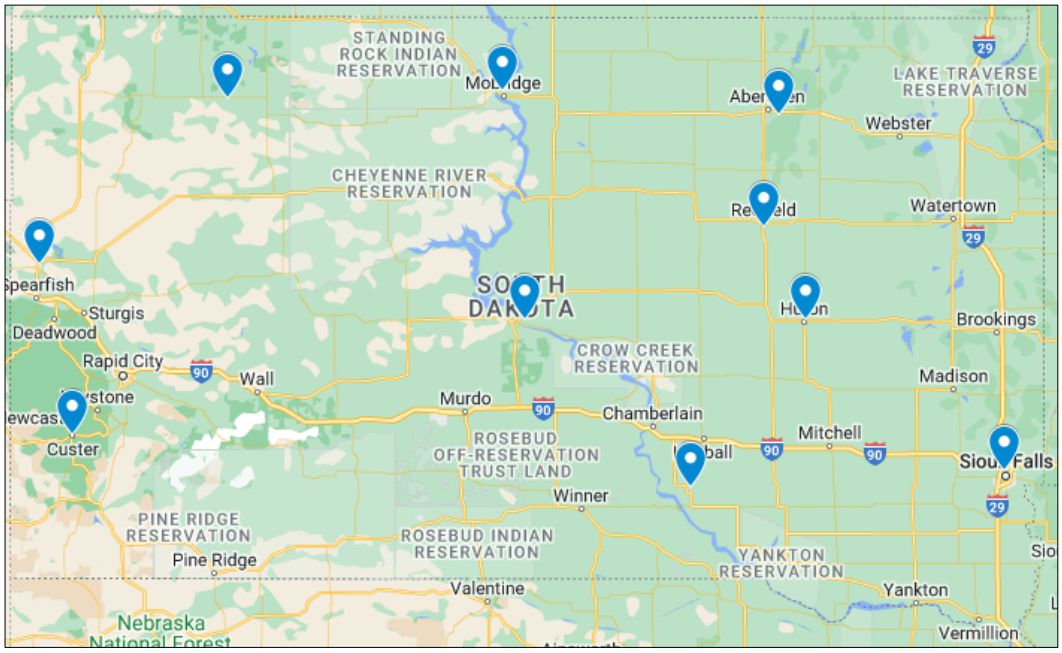


Figure 2. Location of NOAA weather stations in South Dakota.

Figure 2 shows the location of NOAA stations in South Dakota and Figure 3 shows the Zones of South Dakota for expected adverse weather days found from 1998 study (Kenner et al., 1998). The stations have covered all the zones except Zone-3 which is the smallest. The location of NOAA stations based on the zones are listed in Table 7.

Table 7. Location of NOAA stations by zones.

Zones (1998)	NOAA Stations	County (City)
Zone-1	BISON, SD US	Perkins (Bison)
Zone-2	PIERRE REGIONAL AIRPORT, SD US MOBRIDGE 2 NNW, SD US BELLE FOURCHE, SD US	Hughes (Pierre), Walworth (Mobridge), Butte (Belle Fourche)
Zone-4	CUSTER, SD US	Custer (Custer City)
Zone-5	ACADEMY 2 NE, SD US HURON REGIONAL AIRPORT, SD US ABERDEEN REGIONAL AIRPORT, SD US REDFIELD, SD US	Charles Mix (Academy), Beadle (Huron), Brown (Aberdeen) Spink (Redfield)
Zone-6	SIOUX FALLS FOSS FIELD, SD US	Minnehaha (Sioux Falls)

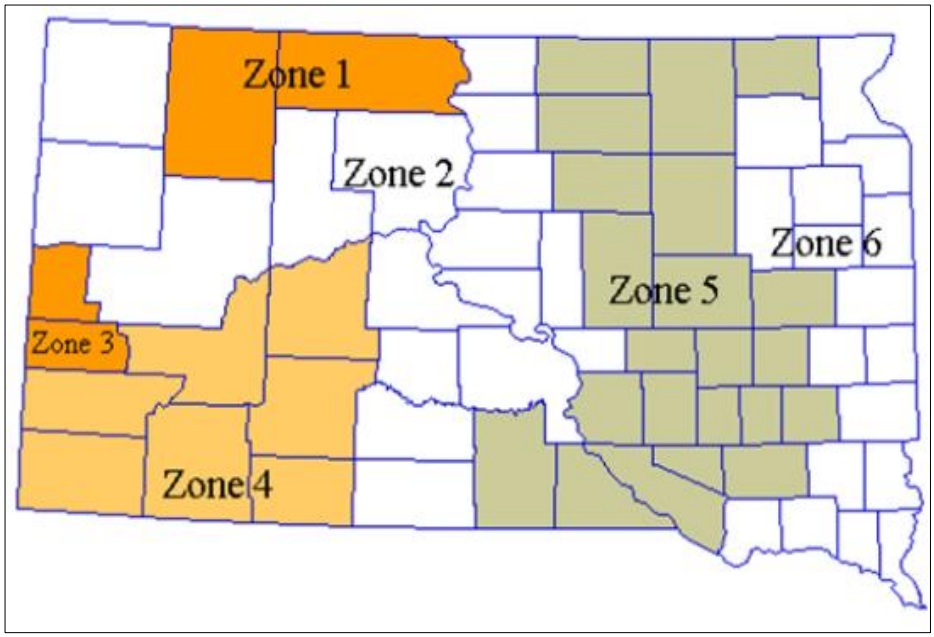


Figure 3. Zones of South Dakota for expected adverse weather days (Kenner et al., 1998).

The thesis is only focused on the effect of air temperature on asphalt paving of the road construction works in South Dakota. From the NOAA data, two types of temperature data are obtained. They are maximum air temperature and minimum air temperature. According to the Standard Spec Book (South Dakota DOT, 2015) of South Dakota, asphalt concrete shall not be placed when the underlying surface is wet or frozen. Also, the minimum air and surface temperature in the shade is 45°F and 40°F when the compacted thickness of surface course is 1 inch or less and over 1 inch respectively (South Dakota DOT, 2015). For the thesis, it is assumed that the asphalt paving works will be conducted during daylight, and when the air temperature is mostly higher than the rest of the days. For this reason, the maximum air temperature data is used for the analysis. Also, the term 'maximum temperature' (TMAX) is used for the rest of the thesis to represent maximum air temperature.

2.3. Descriptive Data Analysis for Maximum Temperature

Table 8 shows the descriptive data analysis for maximum temperature at all 10 NOAA stations. It has the project location, NOAA station name, start and end date for the maximum temperature data, the number of days that have the maximum temperature data within the period, and the corresponding coverage (in percentage). Mobridge and Redfield, and Belle Fourche stations have 77.8%, 85.1%, and 88.9% of maximum temperature data coverage. The other stations have more than 90% data coverage. The NOAA stations at Aberdeen, Huron, Pierre, and Sioux Falls have 100% maximum temperature data coverage.

Table 8. Descriptive data analysis for maximum temperature.

Sl.	County (City)	NOAA Station Name	Maximum Temperature (TMAX)				
			Start Date	End Date	Days	Data	Coverage
1	Hughes (Pierre)	PIERRE REGIONAL AIRPORT, SD US	1/1/1991	12/31/2020	10958	10954	100.0%
2	Charles Mix (Academy)	ACADEMY 2 NE, SD US	1/1/1991	12/31/2020	10958	10850	99.0%
3	Spink (Redfield)	REDFIELD, SD US	1/1/1991	4/30/2011	7425	6317	85.1%
4	Beadle (Huron)	HURON REGIONAL AIRPORT, SD US	1/1/1991	12/31/2020	10958	10958	100.0%
5	Brown (Aberdeen)	ABERDEEN REGIONAL AIRPORT, SD US	1/1/1991	12/31/2020	10958	10958	100.0%
6	Minnehaha (Sioux Falls)	SIOUX FALLS FOSS FIELD, SD US	1/1/1991	12/31/2020	10958	10958	100.0%
7	Walworth (Mobridge)	MOBRIDGE 2 NNW, SD US	1/1/1991	12/31/2020	10958	8530	77.8%
8	Butte (Belle Fourche)	BELLE FOURCHE, SD US	1/1/1991	12/31/2020	10958	9743	88.9%
9	Custer (Custer City)	CUSTER, SD US	1/1/1991	12/31/2020	10958	10249	93.5%
10	Perkins (Bison)	BISON, SD US	1/1/1991	12/31/2020	10958	10734	98.0%

Table 9 shows the coverage of available maximum temperature data for every 5-year cycle from 1991 to 2020. The NOAA station at Mobridge shows the lowest (77.8%) coverage of data since it has missing data from 10/01/1997 to 02/29/2004. But it has good data coverage in the recent years (2006 to 2020). However, the NOAA station at Redfield (USC00397052) has no data from 2012 to 2020. This station is omitted from the analysis of NOAA data for the following reasons:

(i) This station is in the North-East of South Dakota. But the 'ABERDEEN REGIONAL AIRPORT, SD US' (USW00014929) station is also in the North-East of South Dakota, and it has 100% data coverage.

(ii) The 'REDFIELD, SD US' (USC00397052) station has data from 01/01/1991 to 04/30/2011. So, it has very low coverage of the most recent (2011-2020) data. On the other hand, the 'MOBRIDGE 2 NNW, SD US' (USC00395691) station has less data coverage than the 'REDFIELD, SD US' (USC00397052) station. But the Mobridge station has very high coverage of the most recent (2006-2020) data. That is why, the 'MOBRIDGE 2 NNW, SD US' (USC00395691) station is used in the data analysis. But the 'REDFIELD, SD US' (USC00397052) station is omitted from the NOAA data analysis.

Table 9. Coverage of available data for maximum temperature.

Sl.	NOAA Station Name	Coverage of Available Data for Maximum Temperature					
		1991-1995	1996-2000	2001-2005	2006-2010	2011-2015	2016-2020
1	PIERRE REGIONAL AIRPORT, SD US	100.0%	99.9%	100.0%	100.0%	100.0%	99.9%
2	ACADEMY 2 NE, SD US	100.0%	100.0%	98.3%	95.8%	99.9%	100.0%
3	REDFIELD, SD US	98.2%	76.8%	64.6%	99.7%	6.6%	0.0%
4	HURON REGIONAL AIRPORT, SD US	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
5	ABERDEEN REGIONAL AIRPORT, SD US	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
6	SIOUX FALLS FOSS FIELD, SD US	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
7	MOBRIDGE 2 NNW, SD US	99.9%	35.0%	36.9%	100.0%	100.0%	95.3%

Sl.	NOAA Station Name	Coverage of Available Data for Maximum Temperature					
		1991-1995	1996-2000	2001-2005	2006-2010	2011-2015	2016-2020
8	BELLE FOURCHE, SD US	96.5%	96.2%	74.1%	72.5%	99.1%	95.0%
9	CUSTER, SD US	98.3%	99.6%	82.2%	85.0%	97.6%	98.5%
10	BISON, SD US	98.0%	99.7%	93.9%	96.3%	99.9%	99.9%

2.4. Threshold Violation Day

When the maximum temperature (TMAX) of a day is below a certain threshold maximum temperature, that day is counted as a threshold violation (TV) day. For example, the threshold maximum temperature is set as 40°F. If the maximum temperature of a day is 37°F, which is below 40°F, then that day is considered as a threshold violation day.

2.5. Data Processing in MS Excel for Analysis

The weather data downloaded from the NOAA website are in comma-separated values (csv) file format. These data are imported into an Excel file. Since the thesis is only dealing with maximum temperature, the other weather data (average and minimum temperature, precipitation, wind speed, evaporation, soil temperature, sunshine, sky cover & clouds, weather type etc.) are deleted from the Excel file. So, the Excel file contains the following data: NOAA Station ID, Station Name, Latitude, Longitude, and Elevation of Station, Date of data collection, and maximum temperature.

There are 9 NOAA stations considered for the analysis of the thesis. The data of each NOAA station is copied to a new tab. So, there are 9 tabs that contain data of each NOAA station separately. The tabs are renamed to their corresponding NOAA Station ID. Within each tab, the data are then separated by year from 1991 to 2020. They are

arranged in such a manner that each column contains data of one year, and the columns are arranged side-by-side from left to right. The far-left column has the maximum temperature data of 1991, and the far-right column has the maximum temperature data of 2020. So, there are 30 columns in each tab and each column contains data of one year. In order to facilitate the use of the same formula for all the years, a missing day is inserted for February 29th for non-leap years.

There are different threshold maximum temperatures used during the summary calculation to check how much they vary for different thresholds. Table 10 shows the annual threshold violation (TV) days in 1991 at ACADEMY 2 NE, SD US (USC00390043) Station for different thresholds (0°F, 20°F, 32°F, 40°F, 45°F, 50°F, 60°F, 80°F, 99°F, 100°F).

Table 10. Threshold violation days in 1991 at different threshold maximum temperatures at Academy NOAA station.

Threshold TMAX (°F)	TV Days	Cumulative TV Days	% of Cumulative TV Days
0.00	0	0	0.00%
20.00	20	20	5.48%
32.00	17	37	10.14%
40.00	42	79	21.64%
45.00	30	109	29.86%
50.00	26	135	36.99%
60.00	35	170	46.58%
80.00	97	267	73.15%
99.00	85	352	96.44%
100.00	13	365	100.00%

From Table 10, it is found that when the threshold is set at 0°F, there was no day in 1991 that had maximum temperature (TMAX) less than the threshold (0°F in this

case). The formula used in Excel is: ‘=COUNTIF(M$3:M$368,CONCAT("<",I371))’. It means that if a value in the TMAX range is less than 0, it is included in the count.

When the threshold is increased to 20°F, then there were 20 days in 1991 that had TMAX less than 20°F. The formula used in Excel is: ‘=COUNTIF(M$3:M$368,CONCAT("<",I372))-N371’. It means that if a value in the TMAX range is less than 20, it is included in the count and then the cumulative count for those less than 0 are subtracted.

When the threshold is set as 32°F, then there were 37 days in 1991 that had TMAX less than 32°F. Also, there were 17 days that had TMAX equal or greater than 20°F but less than 32°F. The formula used in Excel is: ‘=COUNTIF(M$3:M$368,CONCAT("<",I373))-N372’. It means that if a value in the TMAX range is less than 32, it is included in the count and then the cumulative count for those less than 20 are subtracted.

Similarly, the threshold violation days are calculated for thresholds 40°F, 45°F, 50°F, 60°F, 80°F.

When the threshold is set as 99°F, then there were 352 days in 1991 that had TMAX less than or equal to 99°F. Also, there were 85 days that had TMAX equal or greater than 80°F but less than or equal to 99°F. The formula used in Excel is: ‘=COUNTIF(M$3:M$368,CONCAT("<=",I379)) - N378’. It means that if a value in the TMAX range is less than or equal to 99, it is included in the count and then the cumulative count for those less than 80 are subtracted.

When the threshold is set as 100°F, then there were 13 days that had TMAX equal or greater than 100°F. The formula used in Excel is: '=COUNTIF(M$3:M$368,CONCAT(">=",I380))'. It means that if a value in the TMAX range is greater than or equal to 100, it is included in the count and then the cumulative count for those less than or equal to 99 are subtracted.

The above-mentioned process is done for one site for one year for all months (January to December) and then copied to all other years (1992-2020) within that NOAA station. Again, the computation of threshold violation days for one site is then copied to all other sites as all were formatted similarly (i.e., with the inserted missing value for February 29th for non-leap years).

From above, the number of threshold violation days are found for different threshold values such as 0°F, 32°F, 35°F, 40°F, 45°F, and so on. The threshold violation days are found for 12 months (January to December) of each year (1991 to 2020) at all 9 NOAA stations. It is found from the Standard Spec Book (South Dakota DOT, 2015) of South Dakota that the minimum air and surface temperature in the shade is 45°F and 40°F when the compacted thickness of surface course is 1 inch or less and over 1 inch respectively. That is why 40°F and 45°F are used as threshold for the analysis.

2.6. 30-Year (1991-2020) Average Threshold Violation Days

For the analysis, the number of threshold violation (TV) days for 40°F and 45°F are used. They are found from the above-mentioned process. For example, the number of threshold (45°F) violation days in January for each year are listed in Table 11 for the HURON REGIONAL AIRPORT, SD US (USW00014936) station:

Table 11. Threshold (45°F) violation days in January at Huron station.

Year	TV Days	Year	TV Days	Year	TV Days
1991	30	2001	31	2011	31
1992	23	2002	25	2012	22
1993	29	2003	27	2013	30
1994	31	2004	28	2014	30
1995	31	2005	28	2015	25
1996	27	2006	27	2016	31
1997	31	2007	31	2017	31
1998	29	2008	29	2018	27
1999	31	2009	30	2019	31
2000	30	2010	31	2020	31

By averaging the threshold violation days of Table 11, it is found that the 30-Year (1991-2020) average threshold (45°F) violation days in January is 28.9 for Huron Station (USW00014936). In this way, the 30-Year (1991-2020) average threshold (45°F) violation days in January for each NOAA station is calculated. They are listed in Table 12.

Table 12. 30-Year (1991-2020) average TV days in January for NOAA stations.

Sl.	Station Name	County (City)	30-Year Average TV Days in January
1	SIOUX FALLS FOSS FIELD	Minnehaha (Sioux Falls)	29.0
2	HURON REGIONAL AIRPORT	Beadle (Huron)	28.9
3	ABERDEEN REGIONAL AIRPORT	Brown (Aberdeen)	29.9
4	ACADEMY 2 NE	Charles Mix (Academy)	25.0
5	PIERRE REGIONAL AIRPORT	Hughes (Pierre)	26.8
6	MOBRIDGE 2 NNW	Walworth (Mobridge)	22.2
7	BISON	Perkins (Bison)	26.5
8	CUSTER	Custer (Custer City)	22.6
9	BELLE FOURCHE	Butte (Belle Fourche)	18.4
		Average =	25.5

By repeating the above-mentioned process, the 30-year (1991-2020) average threshold violation days for every month (January to December) are calculated at all 9 NOAA stations. It is done for both threshold maximum temperatures (40°F and 45°F).

Again, the 30-year (1991-2020) average threshold violation days for South Dakota in a given month are determined by averaging the 30-year (1991-2020) average threshold violation days over all 9 NOAA stations for that month. For example, Table 12 shows the 30-Year (1991-2020) average threshold (45°F) violation days in January for each NOAA station. By averaging these days, the 30-year (1991-2020) average threshold violation days in January for South Dakota is found 25.5. By repeating this process, the 30-year (1991-2020) average threshold violation days for every month (January to December) are calculated for the State of South Dakota. It is done for both threshold maximum temperatures (40°F and 45°F).

Similarly, the average annual threshold violation days are calculated for all 9 NOAA stations. For example, the threshold violation days for each year are listed in Table 13 for the ABERDEEN REGIONAL AIRPORT, SD US (USW00014929) station.

Table 13. Threshold (45°F) violation days by year at Aberdeen station.

Year	TV Days	Year	TV Days	Year	TV Days
1991	124	2001	140	2011	136
1992	132	2002	129	2012	105
1993	138	2003	139	2013	161
1994	129	2004	113	2014	142
1995	145	2005	114	2015	106
1996	147	2006	128	2016	107
1997	156	2007	136	2017	113
1998	124	2008	145	2018	156
1999	102	2009	132	2019	159
2000	124	2010	129	2020	133

By averaging the threshold violation days of Table 13, it can be found that the 30-Year (1991-2020) average annual threshold (45°F) violation days is 131.5 for Aberdeen Station (USW00014929). In this way, the 30-Year (1991-2020) average annual threshold (45°F) violation days for each NOAA station is calculated. They are listed in Table 14.

Table 14. 30-year (1991-2020) average annual TV days for NOAA stations.

Sl.	Station Name	County (City)	30-Year Average Annual TV Days
1	SIOUX FALLS FOSS FIELD	Minnehaha (Sioux Falls)	120.4
2	HURON REGIONAL AIRPORT	Beadle (Huron)	120.9
3	ABERDEEN REGIONAL AIRPORT	Brown (Aberdeen)	131.5
4	ACADEMY 2 NE	Charles Mix (Academy)	108.5
5	PIERRE REGIONAL AIRPORT	Hughes (Pierre)	110.7
6	MOBRIDGE 2 NNW	Walworth (Mobridge)	98.7
7	BISON	Perkins (Bison)	112.6
8	CUSTER	Custer (Custer City)	104.9
9	BELLE FOURCHE	Butte (Belle Fourche)	79.3

The 30-year (1991-2020) average annual threshold violation days are calculated for both threshold maximum temperatures (40°F and 45°F).

On the other hand, the 30-year (1991-2020) average threshold violation days are calculated for each zone (Zone-1, 2, 4, 5, 6) both annually and monthly. Each of Zone-1, 4, and 6 has one representative NOAA station. So, for these zones, the 30-year average threshold violation days for the zone is the same as that of the corresponding NOAA station. But each of Zone-2 and Zone-5 has 3 representative NOAA stations. For these two zones, the 30-year average threshold violation days is calculated by taking average of the 30-year (1991-2020) average threshold violation days of the NOAA stations located

in that zone. For example, the 30-Year (1991-2020) average annual threshold (45°F) violation days for each zone is listed in Table 15.

Table 15. 30-year (1991-2020) average annual TV (45°F) days for zones.

Zone	Station Name	30-Year Average Annual TV Days	
		NOAA Stations	Zones
Zone-1	BISON	112.6	112.6
Zone-2	PIERRE REGIONAL AIRPORT	110.7	96.2
	MOBRIDGE 2 NNW	98.7	
	BELLE FOURCHE	79.3	
Zone-4	CUSTER	104.9	104.9
Zone-5	ACADEMY 2 NE	108.5	120.3
	HURON REGIONAL AIRPORT	120.9	
	ABERDEEN REGIONAL AIRPORT	131.5	
Zone-6	SIOUX FALLS FOSS FIELD	120.4	120.4

Similarly, the 30-Year (1991-2020) average threshold violation days is calculated for each month (January to December) for each zone. The 30-Year (1991-2020) average threshold violation days for the month of January for each zone is listed in Table 16.

Table 16. 30-year (1991-2020) average TV (45°F) days in January for zones.

Zone	Station Name	30-Year Average TV Days in January	
		NOAA Stations	Zones
Zone-1	BISON	26.5	26.5
Zone-2	PIERRE REGIONAL AIRPORT	26.8	22.5
	MOBRIDGE 2 NNW	22.2	
	BELLE FOURCHE	18.4	
Zone-4	CUSTER	22.6	22.6
Zone-5	ACADEMY 2 NE	25.0	27.9
	HURON REGIONAL AIRPORT	28.9	
	ABERDEEN REGIONAL AIRPORT	29.9	
Zone-6	SIOUX FALLS FOSS FIELD	29.0	29.0

The 30-year (1991-2020) average threshold violation days at all zones (Zone-1, 2, 4, 5, 6) are calculated for both threshold maximum temperatures (40°F and 45°F).

2.7. Yearly and Monthly Average Threshold Violation Days

From 1991 to 2020, the average annual threshold violation days are calculated for every year. The number of TV days has already been calculated for every year from 1991 to 2020. The TV days for all 9 NOAA stations are averaged for a given year to determine the average annual TV days for that year. For example, for the year 1991, the threshold (45°F) violation days for each site are shown in Table 17. The average number of TV days is calculated as 112.8 in 1991. This is the average annual TV days in 1991 for the State of South Dakota. This process is repeated for the rest 29 years (1992 to 2020), and it is done for both threshold maximum temperatures (40°F and 45°F).

Table 17. Threshold (45°F) violation days in 1991 for NOAA stations.

Sl.	Station Name	Number of TV Days in 1991
1	SIOUX FALLS FOSS FIELD	117
2	HURON REGIONAL AIRPORT	114
3	ABERDEEN REGIONAL AIRPORT	124
4	ACADEMY 2 NE	109
5	PIERRE REGIONAL AIRPORT	112
6	MOBRIDGE 2 NNW	125
7	BISON	113
8	CUSTER	114
9	BELLE FOURCHE	87
	Average TV Days in 1991 =	112.8

Similarly, from 1991 to 2020, the average threshold violation days of every month (January to December) are calculated for every year. The number of TV days of every month has already been calculated for every year from 1991 to 2020. The TV days for all

9 NOAA stations are averaged for a given month of a given year to determine the average TV days of the month for that year. For example, for the month of January in 1991, the threshold (45°F) violation days for each site are shown in Table 18. The average threshold (45°F) violation days for January is calculated as 28.6 in 1991. This process is repeated for the rest 29 years (1992 to 2020), and it is done for both threshold maximum temperatures (40°F and 45°F). Also, the process is repeated for other months (February to December) as well.

Table 18. Threshold (45°F) violation days for January in 1991 at NOAA stations.

Sl.	Station Name	Number of TV Days for January in 1991
1	SIOUX FALLS FOSS FIELD	31
2	HURON REGIONAL AIRPORT	30
3	ABERDEEN REGIONAL AIRPORT	30
4	ACADEMY 2 NE	28
5	PIERRE REGIONAL AIRPORT	29
6	MOBRIDGE 2 NNW	30
7	BISON	29
8	CUSTER	25
9	BELLE FOURCHE	25
Average TV Days for January in 1991 =		28.6

2.8. 7-Year Moving Average Threshold Violation Days

One Study (Puetz, 2013, pp. 242-253) done for South Dakota indicates the use of the 7-year moving average for weather data to understand the trend. That is why the 7-year moving average is used for the thesis to understand the trend of threshold violation days.

The average threshold violation days for each year have already been calculated both annually and monthly. The 7-year moving average (MA) threshold violation days

are calculated by averaging threshold violation days during the first 7 years, from 1991 to 1997, and then repeating the process for the following 7 years, from 1992 to 1998, 1993 to 1999, and so forth, until 2014 to 2020. So, when it is mentioned as 7-year moving average TV days for the year 1997, it implies that the average TV days are from 1991 to 1997.

Table 19 represents the average annual threshold (45°F) violation days from 1991 to 2000. These days are averaged over all the 9 NOAA stations for each year. Then, the 7-year moving average (MA) annual threshold violation (TV) days for the year 1997 is calculated by averaging the average annual TV days from 1991 to 1997. Similarly, it is calculated for 1998, 1999, and 2000. In the analysis, the 7-year moving average threshold violation days are calculated up to 2020.

Table 19. 7-year moving average annual threshold (45°F) violation days.

Year	Average Annual TV Days	7-Year Period	7-Year MA Annual TV Days
1991	112.8	1991-1997	119.1
1992	112.9	1992-1998	116.5
1993	125.6	1993-1999	110.9
1994	111.4	1994-2000	106.0
1995	119.6		
1996	130.2		
1997	121.6		
1998	94.3		
1999	73.3		
2000	91.6		

Similarly, the 7-year moving average threshold violation days are calculated for every month (January to December) using the same process as described above. Also, the

7-year moving average threshold violation days are calculated for both threshold maximum temperatures (40°F and 45°F).

2.9. 30-Year (1991-2020) Average Maximum Temperature (TMAX)

The computation of the average maximum temperature (TMAX) in a given month of the year involves adding up all the available TMAX data (omitting missing data) for that month and dividing the total by the number of days for which data were available. For instance, the average TMAX at NOAA station HURON REGIONAL AIRPORT (USW00014936) is 61.4°F for April 1991. It is found by averaging all the available TMAX data for April in 1991 at NOAA station USW00014936. By following this process, the average TMAX is calculated for every month (January to December) of every year (1991-2020) at all 9 NOAA stations. For example, the average maximum temperature in January for each year is listed in Table 20 for the HURON REGIONAL AIRPORT, SD US (USW00014936) station:

Table 20. Average maximum temperature in January at Huron station.

Year	Average TMAX (°F)	Year	Average TMAX (°F)	Year	Average TMAX (°F)
1991	23.9	2001	27.1	2011	18.9
1992	36.5	2002	33.1	2012	35.3
1993	25.1	2003	28.6	2013	26.2
1994	13.6	2004	24.1	2014	27.5
1995	24.2	2005	24.8	2015	28.7
1996	19.3	2006	37.9	2016	25.4
1997	17.6	2007	25.5	2017	24.8
1998	26.2	2008	25.6	2018	27.2
1999	24.1	2009	23.0	2019	23.1
2000	31.3	2010	18.6	2020	25.2

By averaging the maximum temperatures of Table 20, it is found that the 30-Year (1991-2020) average maximum temperature in January is 25.7°F for Huron Station

(USW00014936). In this way, the 30-Year (1991-2020) average TMAX in January for each NOAA station is calculated as listed in Table 21.

Table 21. 30-year (1991-2020) average TMAX in January for NOAA stations.

Sl.	Station Name	County (City)	30-Year Average TMAX (°F) in January
1	SIOUX FALLS FOSS FIELD	Minnehaha (Sioux Falls)	26.1
2	HURON REGIONAL AIRPORT	Beadle (Huron)	25.7
3	ABERDEEN REGIONAL AIRPORT	Brown (Aberdeen)	22.5
4	ACADEMY 2 NE	Charles Mix (Academy)	30.0
5	PIERRE REGIONAL AIRPORT	Hughes (Pierre)	29.3
6	MOBRIDGE 2 NNW	Walworth (Mobridge)	24.2
7	BISON	Perkins (Bison)	29.3
8	CUSTER	Custer (Custer City)	37.5
9	BELLE FOURCHE	Butte (Belle Fourche)	35.7

By repeating the above-mentioned process, the 30-year (1991-2020) average maximum temperature for every month (January to December) is calculated at all 9 NOAA stations.

On the other hand, the 30-year (1991-2020) average maximum temperature is calculated for each zone (Zone-1, 2, 4, 5, 6) for every month (January to December). Each of Zone-1, 4, and 6 has one representative NOAA station. So, for these zones, the 30-year average maximum temperature of a given month for the zone is the same as that of the corresponding NOAA station. But each of Zone-2 and Zone-5 has 3 representative NOAA stations. For these two zones, the 30-year average maximum temperature of a given month is calculated by taking average of the 30-year (1991-2020) average maximum temperatures of the corresponding month of the NOAA stations located in that

zone. For example, the 30-Year (1991-2020) average maximum temperature in January for each zone is listed in Table 22.

Table 22. 30-year (1991-2020) average TMAX in January for zones.

Zone	Station Name	30-Year Average TV Days in January	
		NOAA Stations	Zones
Zone-1	BISON	29.3	29.3
Zone-2	PIERRE REGIONAL AIRPORT	29.3	29.7
	MOBRIDGE 2 NNW	24.2	
	BELLE FOURCHE	35.7	
Zone-4	CUSTER	37.5	37.5
Zone-5	ACADEMY 2 NE	30.0	26.1
	HURON REGIONAL AIRPORT	25.7	
	ABERDEEN REGIONAL AIRPORT	22.5	
Zone-6	SIOUX FALLS FOSS FIELD	26.1	26.1

CHAPTER 3: ANALYSIS

The methodology section describes the weather data download, data processing, descriptive data analysis, and computation of threshold violation days. The analysis section focuses on the trend of threshold (both 40°F and 45°F) violation days over 30-Year (1991-2020) period both annually and monthly. Also, the threshold violation days are compared to the expected adverse weather days found from the 1998 study (Kenner et al., 1998). That is why different graphs are plotted for 30-year average threshold violation days, 7-year moving average threshold violation days, and so on. Moreover, it is also analyzed if the maximum temperature data matches the weekly progress report (WPR) data for project sites and their corresponding NOAA stations' data.

3.1. Adverse Weather Days from 1998 South Dakota Study

The number of adverse weather days for surfacing projects is found within the 1998 South Dakota study (Kenner et al., 1998), as shown in Table 23. The Zone columns are from the 1998 study while the AVERAGE column and SUM row were added for analysis purposes. The AVERAGE column represents the average number of adverse weather days for each month statewide across all zones, which will be used later for statewide comparative purposes. The SUM row represents the sum of adverse weather days in a year for each zone. The average number of adverse weather days per year is 101.3 for the State of South Dakota.

There were 6 zones created in the 1998 study. For the current analysis 9 NOAA stations were selected across the State based on the location of the selected project sites for which Weekly Progress Report (WPR) data were available. The selected NOAA stations are located within 5 of the zones from the 1998 Study, as shown in Table 24. The

zones are from the 1998 Study (Kenner et al., 1998) and used in the SDDOT Special Provisions for the SDDOT Standard Specifications (South Dakota DOT, 2015) all over the State of South Dakota.

Table 23. Number of adverse weather days by month for surfacing projects (Kenner et al., 1998).

Month	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	AVERAGE
Jan	18	18	15	16	21	23	18.5
Feb	19	18	12	14	19	21	17.2
Mar	12	10	9	8	10	12	10.2
Apr	5	4	6	4	4	4	4.5
May	5	5	6	4	4	5	4.8
Jun	5	5	5	4	5	6	5.0
Jul	4	4	5	3	4	5	4.2
Aug	3	3	4	3	4	4	3.5
Sep	2	2	3	2	3	4	2.7
Oct	3	3	4	2	3	3	3.0
Nov	11	9	8	7	10	11	9.3
Dec	21	19	15	14	20	22	18.5
SUM	108	100	92	81	107	120	101.3

Table 24. Location of selected NOAA stations.

1998 Zones	NOAA Stations	County (City)
Zone-1	BISON, SD US (USC00390701)	Perkins (Bison)
Zone-2	PIERRE REGIONAL AIRPORT, SD US (USW00024025) MOBRIDGE 2 NNW, SD US (USC00395691) BELLE FOURCHE, SD US (USC00390559)	Hughes (Pierre), Walworth (Mobridge), Butte (Belle Fourche)
Zone-4	CUSTER, SD US (USC00392087)	Custer (Custer City)
Zone-5	ACADEMY 2 NE, SD US (USC00390043) HURON REGIONAL AIRPORT, SD US (USW00014936) ABERDEEN REGIONAL AIRPORT, SD US (USW00014929)	Charles Mix (Academy), Beadle (Huron), Brown (Aberdeen)
Zone-6	SIOUX FALLS FOSS FIELD, SD US (USW00014944)	Minnehaha (Sioux Falls)

3.2. 30-Year (1991-2020) Average Annual Threshold Violation Days

Within Figure 4 the horizontal line (red, solid) at 101.3 days depicts the expected average number of adverse weather days per year for the State of South Dakota determined by the 1998 study (Kenner et al., 1998). The upper varying line (blue, dashed) shows the average annual number of threshold violation days at the 45°F threshold for each NOAA station. The lower varying line (orange, dotted) shows the average annual number of threshold violation days at the 40°F threshold for each NOAA station.

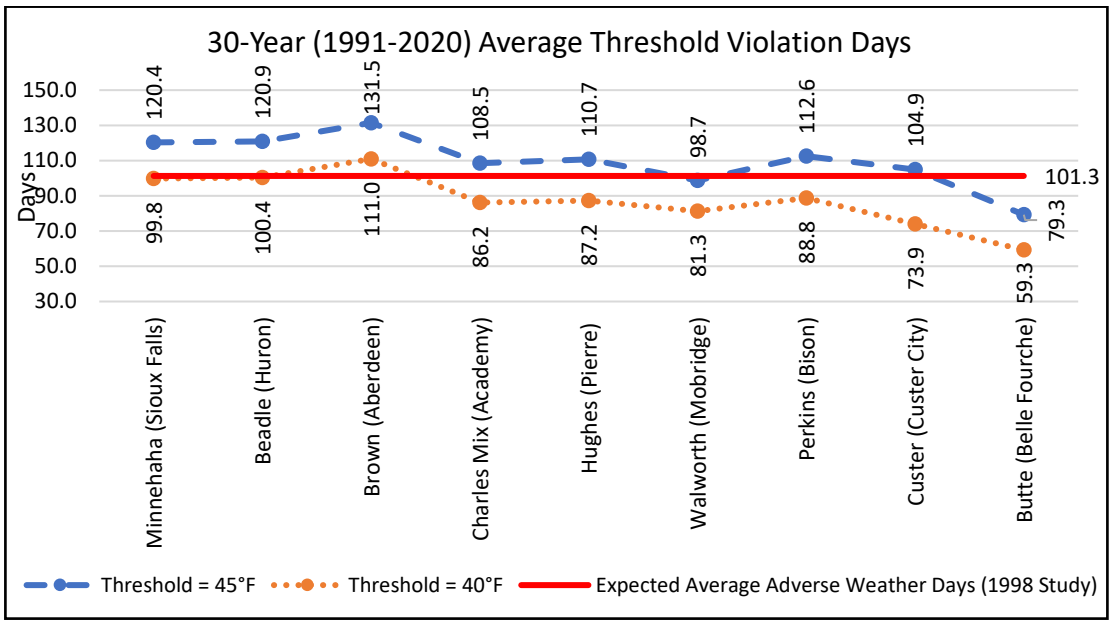


Figure 4. 30-year (1991-2020) average annual threshold violation days by NOAA stations.

Some general observations from Figure 4 include:

- The average number of days with threshold violation decreases when the threshold is reduced from 45°F to 40° F, which is consistent with expectation (i.e., lower temperatures would be met more often).
- The NOAA stations located further east in South Dakota have more threshold violation days than those in the west, decreasing gradually from east to west.

- Generally, the threshold violation days are less than the state average when the threshold maximum temperature is 40°F. Only the Aberdeen NOAA station has more threshold violation days than the state average, while the Sioux Falls and Huron NOAA stations are close to the State Average.
- At the 45°F maximum temperature threshold, most of the NOAA stations have a higher number of threshold violation days than the state average. The exceptions are the Belle Fourche and Mobridge NOAA stations. Belle Fourche has the lowest (80) number of days with threshold (45°F) violation. The stations at Sioux Falls, Huron, Aberdeen, and Pierre have a higher number of days with threshold (45°F) violation. The rest of the NOAA stations have threshold (45°F) violation days close to the state average (101.3).

If instead the NOAA stations were assigned to the zones from the 1998 study, results are as shown in Figure 5. From Figure 3, Zone 3, and part of Zones 1, 2, and 4 are in the west of South Dakota. Similarly, Zones 5 and 6 are in the east of South Dakota. The varying line (red, solid) depicts the expected average number of adverse weather days per year for the State of South Dakota determined by the 1998 study (Kenner et al., 1998). These days are 108, 100, 81, 107, and 120 for Zone 1, 2, 4, 5, and 6 respectively. The rectangular bars (blue, diagonal stripe) of Figure 5 shows the average annual threshold violation days at the 45°F threshold for each NOAA station. The rectangular bars (orange, diamond grid pattern) of Figure 5 shows the average annual threshold violation days at the 40°F threshold for each NOAA station. Some general observations from Figure 5 include:

- From the 1998 study (Kenner et al., 1998), the average threshold violation days vary from zone to zone. Zone 4 has the lowest number of adverse weather days at 81 per year and Zone 6 has the highest with 120 per year.
- Generally, at the 40°F threshold maximum temperature threshold, the average number of days with threshold violation is less than the number of adverse weather days found from 1998 Study, similar to the results from Figure 4. However, again, the opposite is true at the 45°F threshold maximum temperature threshold.

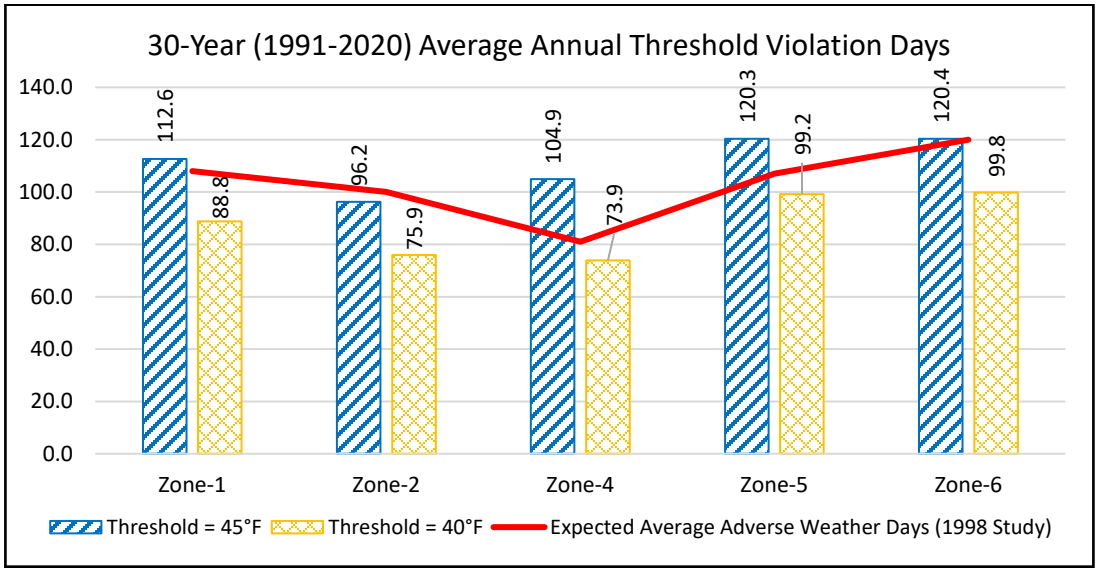


Figure 5. 30-year (1991-2020) average annual threshold violation days by zones.

3.3. Average Annual Threshold Violation Days by Year

Figure 6 shows the average threshold violation days per year for all NOAA stations located all over South Dakota. Similar to Figure 4, the horizontal line (red, solid) at 101.3 days depicts the expected average number of adverse weather days per year for the State of South Dakota determined by the 1998 study (Kenner et al., 1998). The upper varying line (blue, dashed) shows the average annual number of threshold violation days

by year from 1991 to 2020 at the 45°F threshold. The lower varying line (orange, dotted) shows the average annual threshold violation days by year at the 40°F threshold.

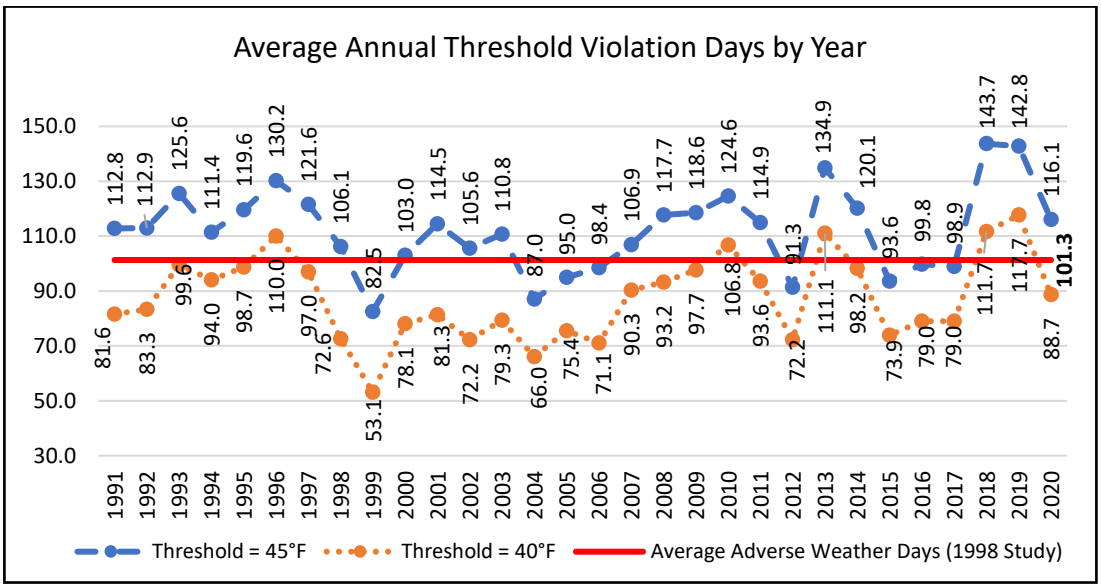


Figure 6. Average annual threshold violation days by year (1991-2020).

Some general observations from the graph include:

- Some years (1999, 2012, 2015) had a sudden decrease in average threshold violation days than the rest of the years.
- On the other hand, some years (2013, 2018) had a sudden increase in average threshold violation days.
- Again, per Figures 4 and 5, the average number of days with threshold violation decreases when the threshold is reduced from 45°F to 40° F, which is consistent with expectation (i.e., lower temperatures would be met more often).
- In general, there is no particular trend displayed in Figure 6. The average threshold (45°F) violation days are higher and always greater than the State Average (101.3) from 1991 to 1997. There is a decreasing trend of average

threshold violation days from 1997 to 1999, an increasing trend from 2004 to 2010.

As Figure 6 shows no clear trend in the yearly average threshold violation days, a 7-year moving average of the threshold violation days over 30 years (1991-2020) is plotted in Figure 7. Similar to Figure 4, the horizontal line (red, solid) at 101.3 days depicts the expected average number of adverse weather days per year for the State of South Dakota determined by the 1998 study (Kenner et al., 1998). The upper varying line (blue, dashed) shows the 7-year moving average annual threshold violation days at the 45°F threshold. The lower varying line (orange, dotted) shows the 7-year moving average annual threshold violation days at the 40°F threshold.

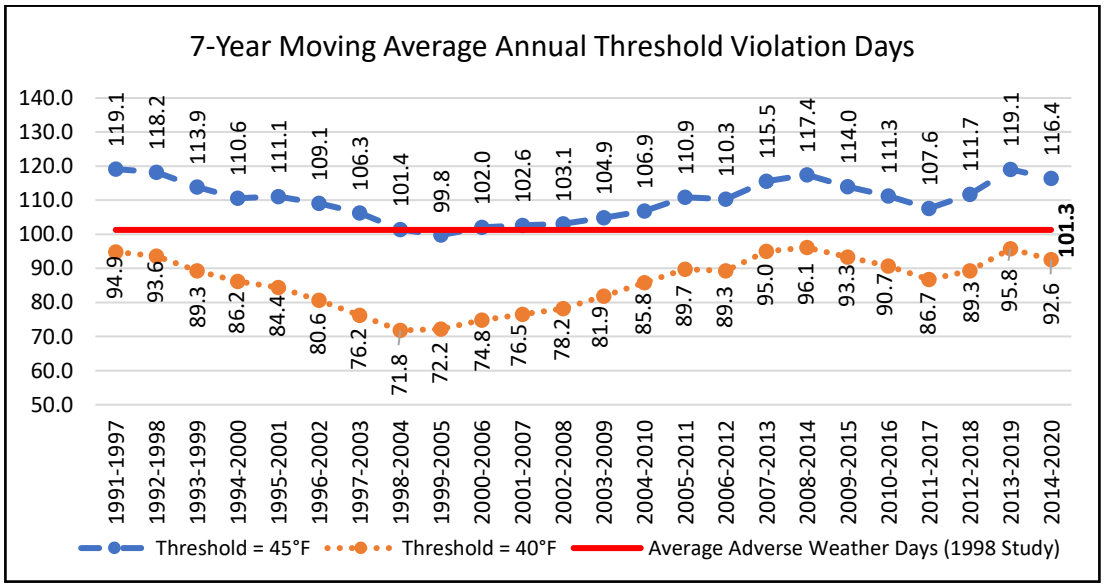


Figure 7. 7-year moving average annual threshold violation days.

When threshold is 45°F, most of the moving average values are generally greater than the State average adverse weather days (101.3). But when threshold is reduced to 40°F, the moving average values are always less than the State average adverse weather

days (101.3). There seems to have been a decreasing trend for the earlier period during the 30 years and a generally increasing trend since.

3.4. Yearly Threshold (45°F) Violation Days by Location of NOAA Stations

The number of days that had maximum temperature less than 45°F per year from 1991 to 2020 are plotted in Figure 8. The plot does not indicate any noticeable trend over the 30-year (1991-2020) period. Some years (1997, 2008, 2013, 2018, 2019) had higher threshold (45°F) violations than the rest of the years and other years (1999, 2004, 2012) had lower threshold violations in most of the sites. Note that the Walworth site has missing data from 1998 through 2003; thus, these data points were excluded from the graph. Generally, Aberdeen station has the highest threshold (45°F) violation days, and the Belle Fourche station has the least threshold (45°F) violation days.

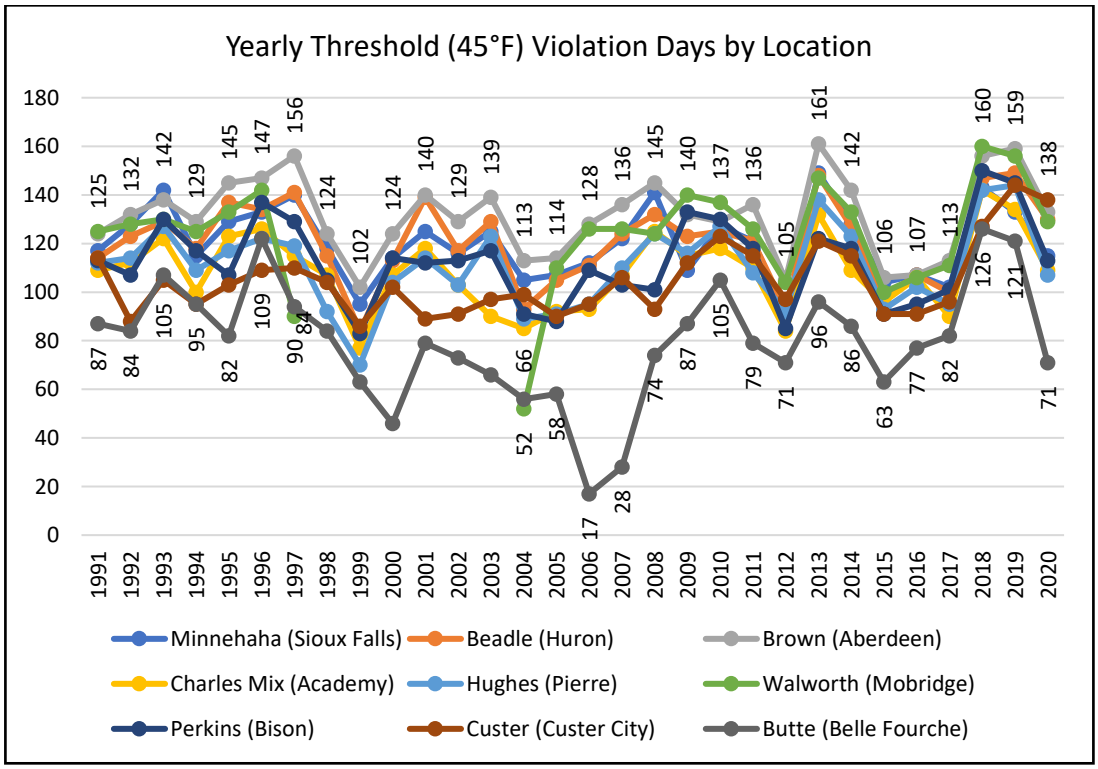


Figure 8. Yearly threshold (45°F) violation days by location of NOAA stations.

3.5. Yearly Threshold (40°F) Violation Days by Location of NOAA Stations

The number of days that had maximum temperature less than 40°F per year from 1991 to 2020 are plotted in Figure 9. The plot does not indicate any noticeable trend over the 30-year (1991-2020) period. Some years (1997, 2008, 2013, 2018, 2019) had higher threshold (40°F) violations than the rest of the years and other years (1999, 2012, 2015) had lower threshold violations in most of the sites. Note that the Walworth site has missing data from 1998 through 2003; thus, these data points were excluded from the graph. Generally, Aberdeen station has the highest threshold (40°F) violation days, and the Belle Fourche station has the least threshold (40°F) violation days.

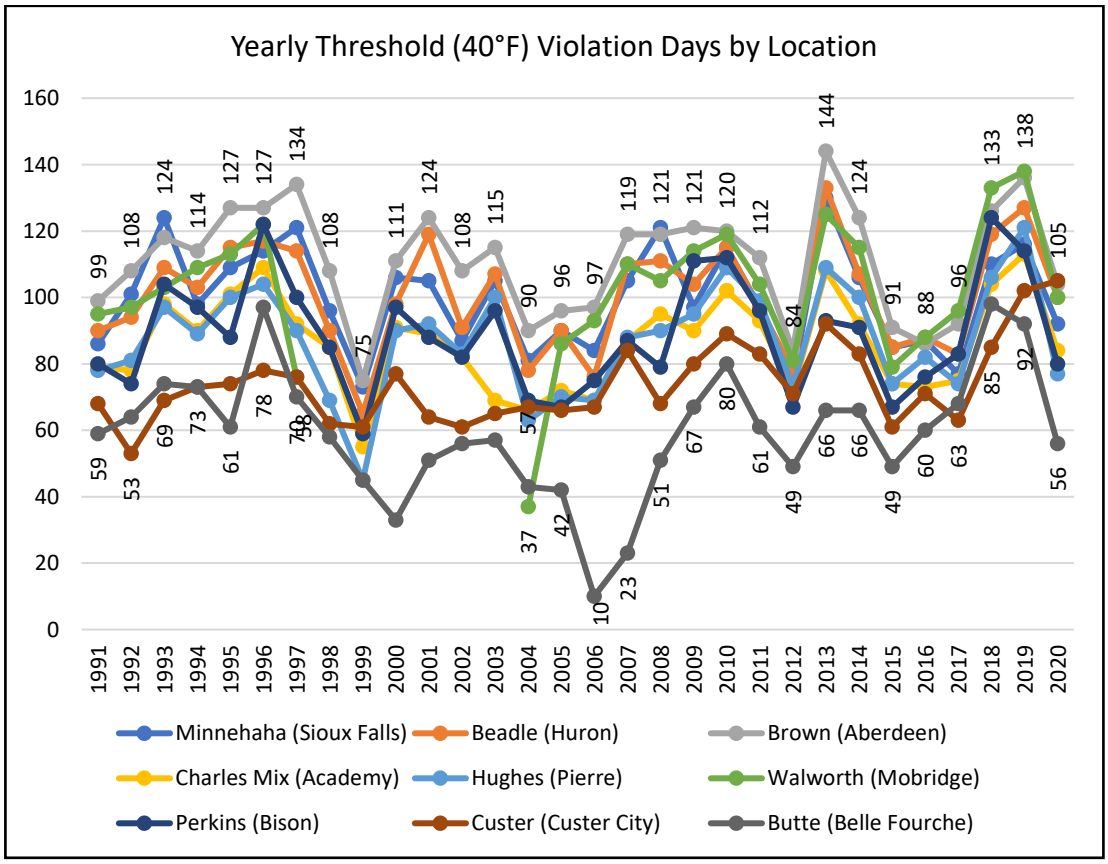


Figure 9. Yearly threshold (40°F) violation days by location of NOAA stations.

3.6. 7-Year Moving Average Annual Threshold (45°F) Violation Days

As no apparent trend is displayed in the yearly threshold (45°F) violation days, a 7-year moving average of the threshold violation days per year is plotted in Figure 10. It shows the 7-year moving average from 1991 to 2020 for NOAA stations at 9 locations. The horizontal line (red, solid) at 101.3 days depicts the expected average number of adverse weather days per year for the State of South Dakota determined by the 1998 study (Kenner et al., 1998).

Most of the chosen NOAA stations generally have more 7-year moving average annual threshold (45°F) violation days than the State Average (101.3). Only the Belle Fourche station always had less 7-year moving average annual threshold (45°F) violation days compared to the State Average (101.3). As the Walworth station does not have maximum temperature data from 1998 to 2003, the moving average only shows those timeframes that do not involve that timeframe. Figure 10 does not show any trend over the 30 years period. The NOAA station at Aberdeen always has the highest 7-year moving average annual threshold (45°F) violation days. The stations at Huron and Sioux Falls have similar 7-year moving average annual threshold (45°F) violation days. Additionally, the NOAA stations at Academy and Custer City have similar 7-year moving average annual threshold (45°F) violation days in the recent years (1998-2020). Similarly, the NOAA stations at Pierre and Bison have similar 7-year moving average annual threshold (45°F) violation days in the recent years (1998-2020). Lastly, the NOAA station at Belle Fourche always has the lowest 7-year moving average threshold (45°F) violation days per year.

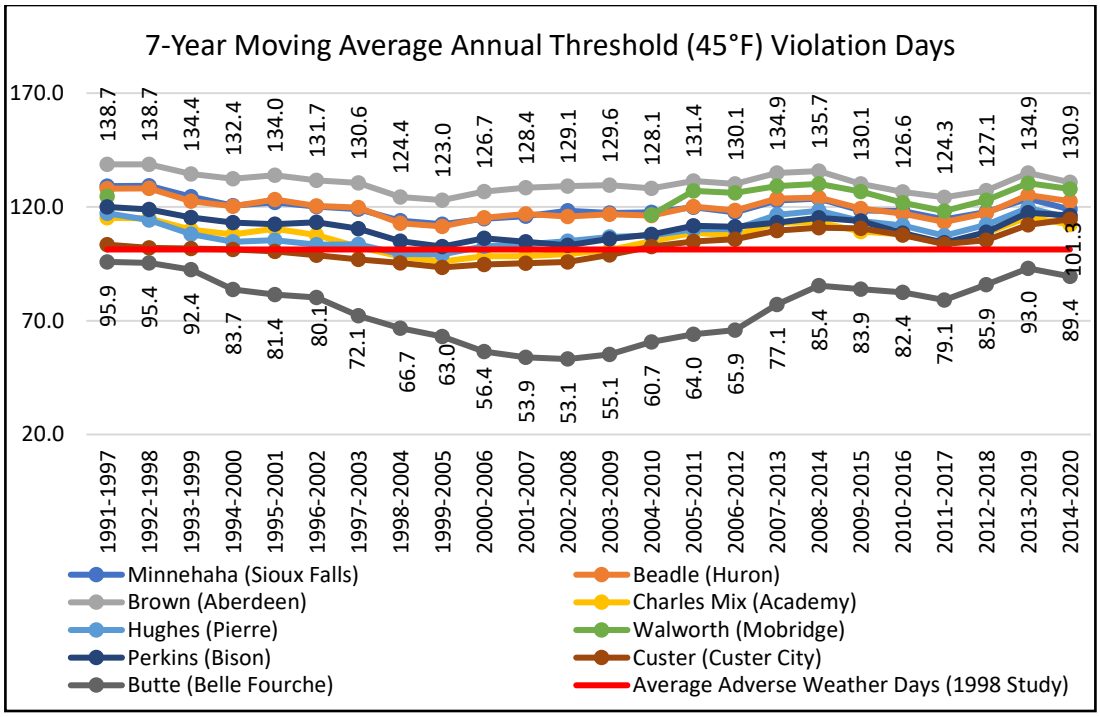


Figure 10. 7-year moving average annual threshold (45°F) violation days.

Figure 11 shows the average threshold (45°F) violation days per year by 7-Year moving average in different zones, as developed during the prior 1998 study, of South Dakota. It does not appear to show any obvious trend over the 30-year period. Particular to zonal groupings:

- Zones 5 and 6, both eastern SD zones, have similar 7-Year moving average annual threshold (45°F) violation days per year. Both are always the highest over the 30-year period. From the 1998 study (Kenner et al., 1998), Zone 5 had 107 annual adverse weather days while Zone 6 had 120. Generally, the Zone 5 violation days based on temperature have been above that level over the 30-year period while the Zone 6 violation days hover around the value indicated from the 1998 study.

- From the previous study (Kenner et al., 1998), Zone 1 had 108 annual adverse weather days. Within Figure 11, initially, Zone 1 experienced higher than those days but trended downward until again trending upward to again above that level.
- Zone 4 had 81 annual adverse weather days per the 1998 study (Kenner et al., 1998). Generally, the threshold violation days have an increasing trend for Zone 4 over the 30-year period.
- Zone 2, which includes only the Walworth station so any average including the 1998-2003 data is suspect, had 100 annual adverse weather days per the 1998 study (Kenner et al., 1998). The threshold violation days display an increasing trend.

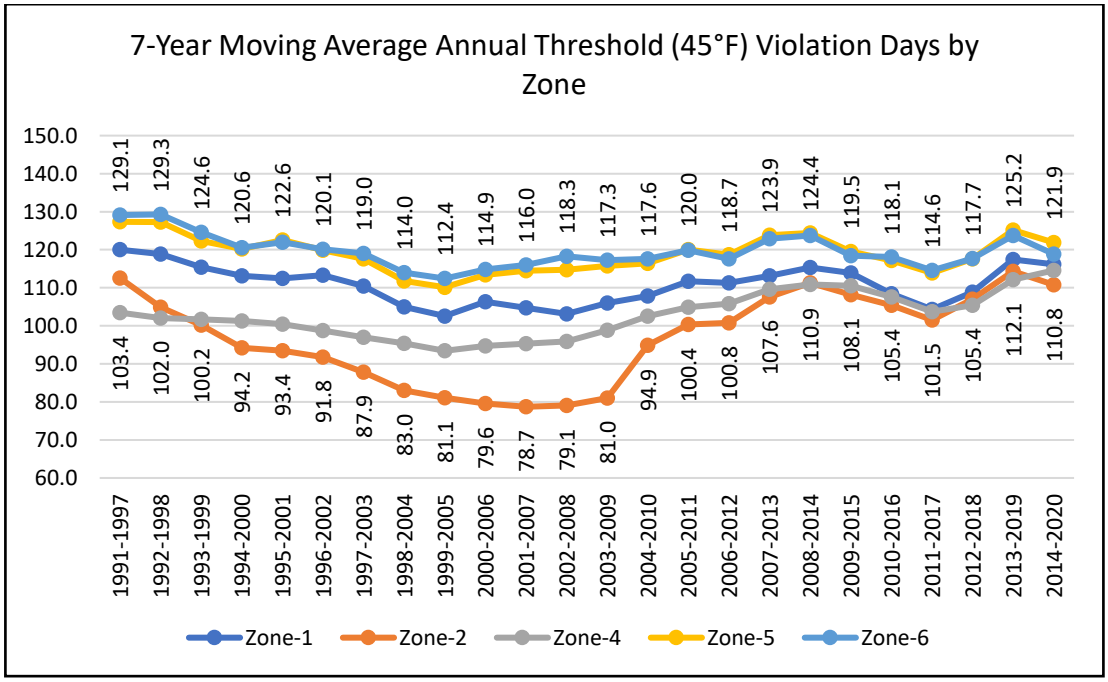


Figure 11. 7-year moving average annual threshold (45°F) violation days in different zones.

3.7. 7-Year Moving Average Annual Threshold (40°F) Violation Days

As no apparent trend is displayed in the yearly threshold (40°F) violation days, a 7-year moving average of the threshold violation days per year is plotted in Figure 12. It shows the 7-year moving average from 1991 to 2020 for NOAA stations at 9 locations. Similar to Figure 1, the horizontal line (red, solid) at 101.3 days depicts the expected average number of adverse weather days per year for the State of South Dakota determined by the 1998 study (Kenner et al., 1998).

Most of the chosen NOAA stations generally have less 7-year moving average annual threshold (40°F) violation days than the State Average (101.3). Only Aberdeen station always had more 7-year moving average annual threshold (40°F) violation days compared to the State Average (101.3). As the Walworth (Mobridge) station does not have maximum temperature data from 1998 to 2003, the moving average only shows those timeframes that do not involve that timeframe. Figure 12 does not show any trend over the 30 years period. The NOAA station at Aberdeen always has the highest 7-year moving average annual threshold (40°F) violation days per year. In contrast, the stations at Academy, Pierre, Bison, Custer City, and Belle Fourche always had less threshold (40°F) violation days compared to the State Average (101.3). The Belle Fourche station had the lowest average threshold (40°F) violation days per year in most of the cases. The Mobridge station shows more threshold (40°F) violation days than the State Average (101.3) in recent years (2005-2020). Lastly, the stations at Huron and Sioux Falls show both higher and lower than the State Average (101.3) threshold (40°F) violation days over the 30-Year period.

The stations at Huron and Sioux Falls have similar moving average threshold (40°F) violation days per year. Similarly, the NOAA stations at Academy, Pierre, and Bison have similar moving average threshold (40°F) violation days over the 30-Year period.

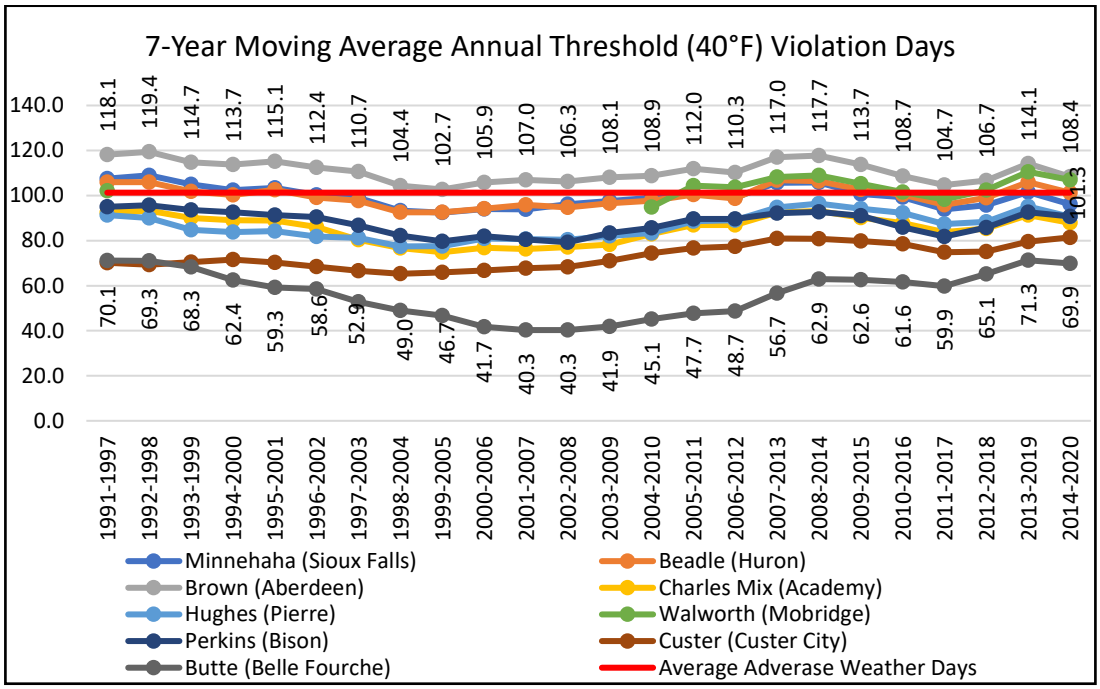


Figure 12. 7-year moving average annual threshold (40°F) violation days.

Figure 13 shows the average threshold (40°F) violation days per year by 7-Year moving average in different zones, as developed during the prior 1998 study, of South Dakota. It does not appear to show any obvious trend over the 30-year period. Particular to zonal groupings:

- Zones 5 and 6, both eastern SD zones, have similar 7-Year moving average annual threshold (40°F) violation days per year. Both are always the highest over the 30-year period. From the 1998 study (Kenner et al., 1998), Zone 5 had 107 annual

adverse weather days while Zone 6 had 120. Generally, Zones 5 and 6 violation days based on temperature have been below that level over the 30-year period.

- From the previous study (Kenner et al., 1998), Zones 1 and 2 had 108 and 100 annual adverse weather days respectively. Zone 2, which includes only the Walworth (Mobridge) station so any average including the 1998-2003 data is suspect. Zones 1 and 2 violation days based on temperature have been below that level (Kenner et al., 1998) over the 30-year period.
- Zone 4 had 81 annual adverse weather days per the 1998 study (Kenner et al., 1998). The threshold violation days are below the number of adverse weather days in most cases. Generally, the threshold violation days have an increasing trend for Zone 4 over the 30-year period.

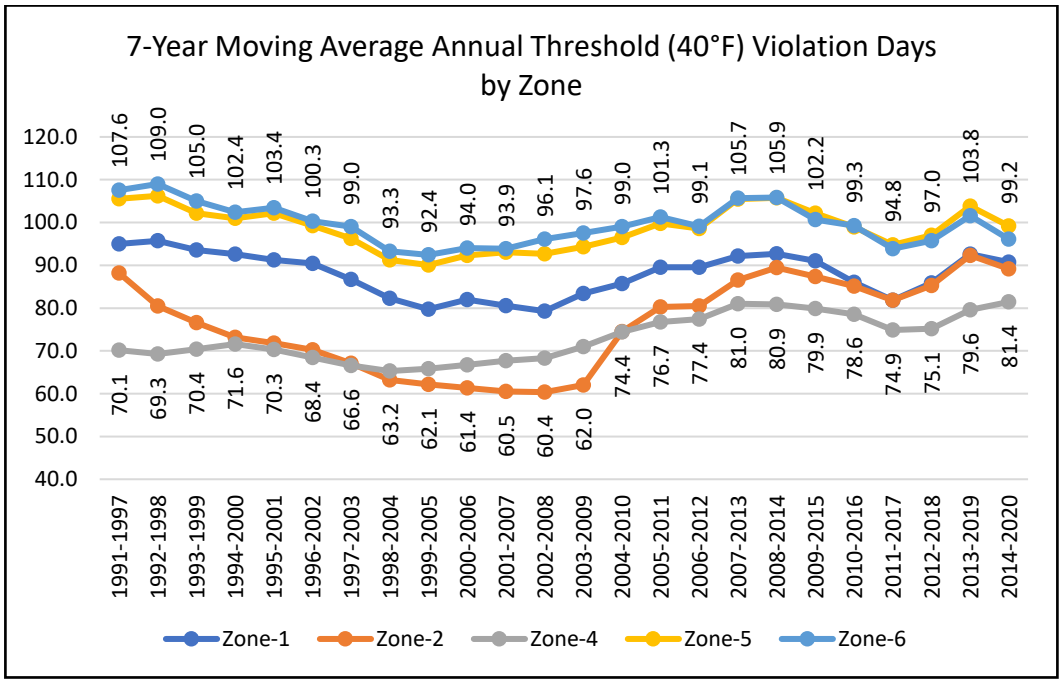


Figure 13. 7-year moving average annual threshold (40°F) violation days in different zones.

3.8. Average Maximum Temperature over 30 Years by Month at NOAA Stations

In Figure 14, the maximum temperatures for each month are averaged over 30 years (1991-2020) period for each NOAA station. As expected, January has the lowest average for all 9 locations, February and December have similar, slightly higher averages, March and November are similar and, again, somewhat higher, with April and October still higher, and May the highest. Although the averages for April and October are close, October is higher across all 9 locations.

For the highest temperature month, May, several stations have similar maximum temperatures, with one grouping including Sioux Falls, Huron, Aberdeen, Academy, and Hughes, another including Mobridge, Bison, and Belle Fourche, and the last consisting of Custer City. The first grouping of sites is at or east of the middle of the State. The second grouping is more westerly and northern. The last is to the far southwest of the State.

For the lowest temperature month, January, these similarity groupings are somewhat different. Keeping in mind some geographic grouping, Sioux Falls and Huron seem to form one group, Aberdeen and Mobridge another, Academy, Pierre, and Bison perhaps another, and Belle Fourche and Custer City perhaps the last. The first group is more south-easterly in the State, the second group northern to the east of the middle half of the State, the third group running through the middle of the State somewhat north-westerly/south-easterly, and the last group comprising the far south-west of the State. This may make sense with the general weather patterns of cold weather during the winter months emanating from Canada. Generally, temperatures warm from east toward west and north towards south.

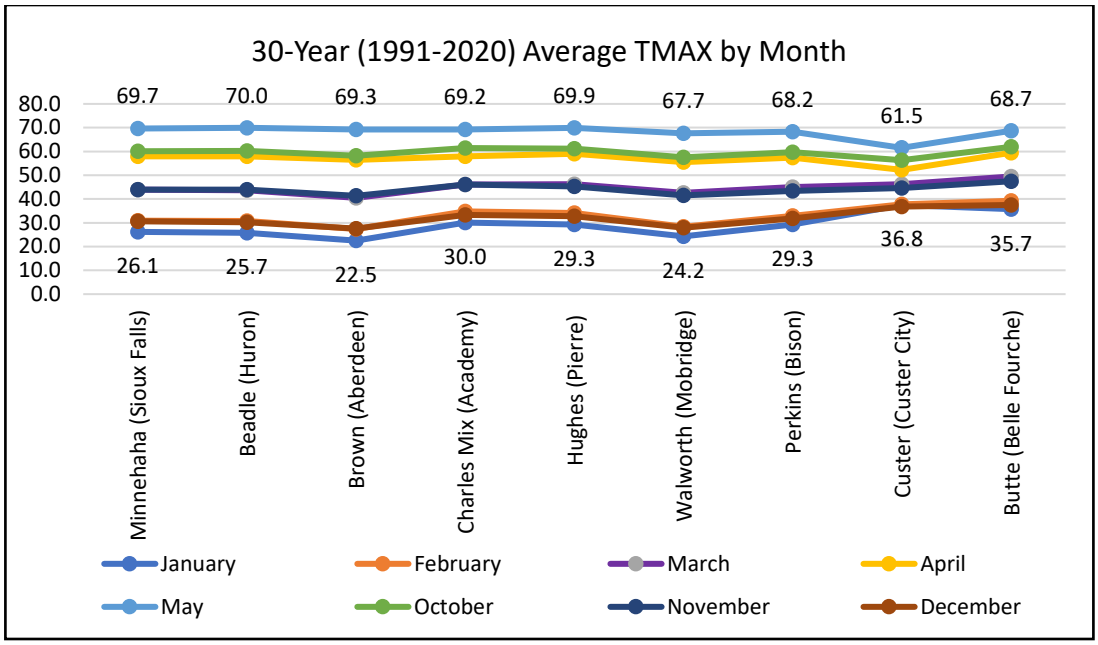


Figure 14. 30-year (1991-2020) average maximum temperature by month.

3.9. Average Threshold Violation Days per Month over 30-Years (1991-2020)

Within Figure 15, the general similarities and number of threshold violation days (both thresholds 45°F and 40°F) follow the pattern of the temperatures, again non unexpectedly. However, the groupings of sites are somewhat different, with a more evident decreasing pattern as the stations move from East to West. The violation days are similar for all months at the Sioux Falls, Huron, Aberdeen, and Mobridge stations. They are in the East and North South Dakota. Similarly, the Academy, Pierre, and Bison stations have similar average threshold violation days across all months. Academy is in Southern part, Pierre is in Central part, and Bison is in North-West part of South Dakota. The Belle Fourche station located in the West of South Dakota has the lowest average threshold violation days for all months.

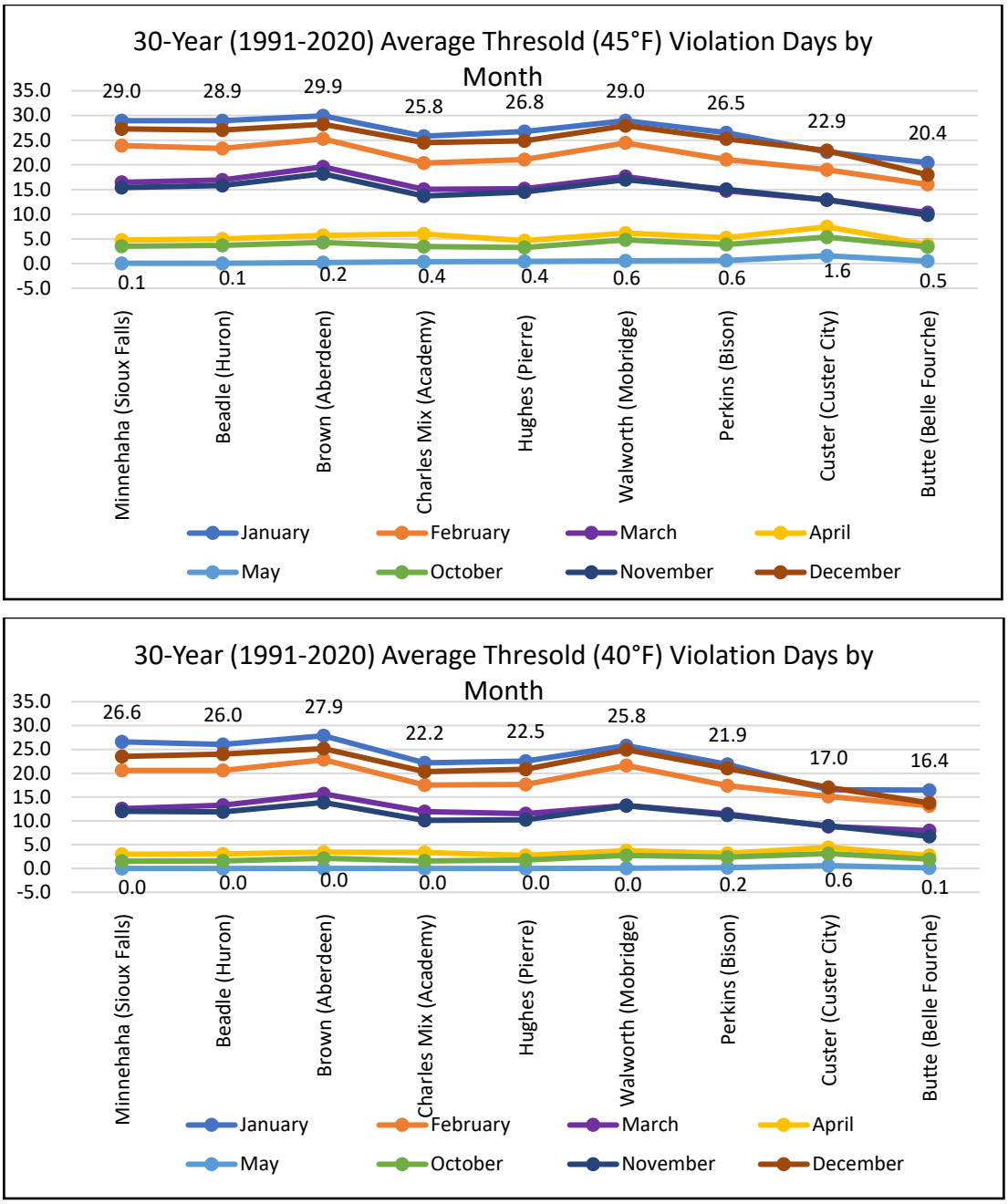


Figure 15. 30-year (1991-2020) average threshold (45°F and 40°F) violation days by month.

3.10. 30-Year (1991-2020) Average Threshold Violation Days by Month

The 30-year average threshold violation days by month are shown in Table 25 and Figure 16, for both the thresholds (45°F and 40°F) as well as the average from the 1998 study. Within Figure 16 the red, solid varying line depicts the expected average number

of adverse weather days by month for South Dakota determined by the 1998 study (Kenner et al., 1998). The blue, dashed varying line shows the average threshold violation days by month at the 45°F threshold. The orange, dotted varying line shows the average threshold violation days by month at the 40°F threshold.

For the months January, February, March, November, and December, the 30-year average threshold violation days are higher than the 1998 average adverse weather days (Kenner et al., 1998) for both thresholds (45°F and 40°F). For all the months except June and July, the threshold violation days are higher at 45°F.

Table 25. 30-year (1991-2020) average threshold violation days by month.

Month	Threshold = 45°F	Threshold = 40°F	Average Adverse Weather Days (1998 Study)
January	26.2	22.9	18.5
February	21.6	18.5	17.2
March	15.4	11.8	10.2
April	5.3	3.2	4.5
May	0.5	0.1	4.8
June	0.1	0.1	5.0
July	0.0	0.0	4.2
August	0.1	0.0	3.5
September	0.6	0.1	2.7
October	3.9	2.0	3.0
November	14.7	10.9	9.3
December	25.1	21.2	18.5

From Table 25, it is obvious that temperature does not have much effect on causing adverse weather day for the months of May, June, July, August, and September. It is found from the Standard Specifications for Roads and Bridges for the State of South Dakota (South Dakota DOT, 2015) that the seasonal limitation for surfacing works is from May 1 to October 15 (inclusive). So, a more detailed analysis for the months of

April and October can provide more information about the threshold violation trends at different locations of South Dakota.

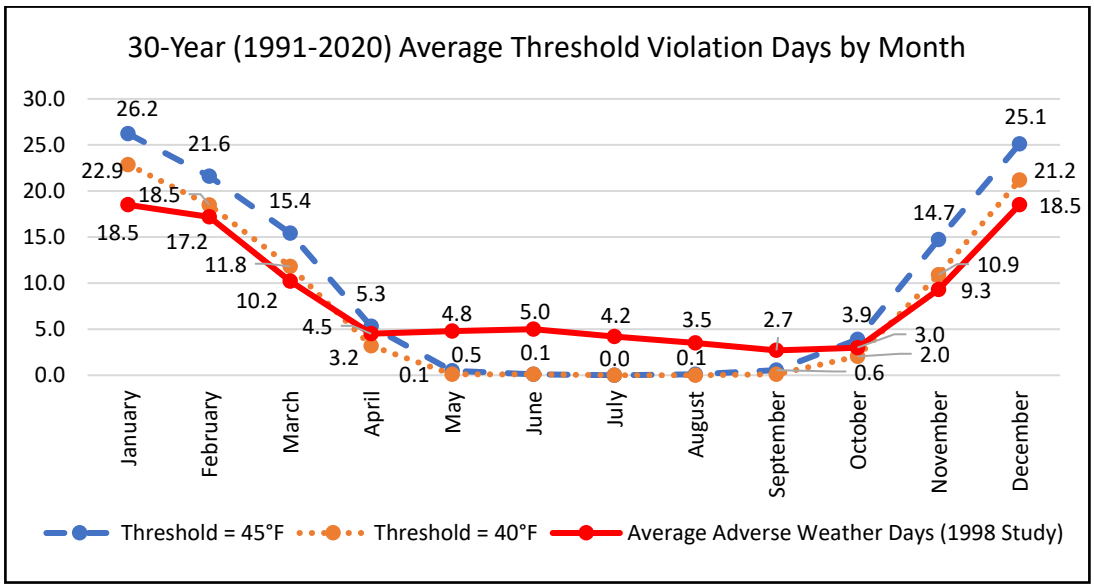


Figure 16. 30-year (1991-2020) average threshold violation days by month.

3.11. 30-Year (1991-2020) Average Threshold Violation Days in April by Location

Within Figure 17 the horizontal line (red, solid) at 4.5 days depicts the expected average number of adverse weather days in April for the State of South Dakota determined by the 1998 study (Kenner et al., 1998). The upper varying line (blue, dashed) shows the average threshold violation days in April at 45°F threshold for each NOAA station. The lower varying line (orange, dotted) shows the average threshold violation days in April at 40°F threshold for each NOAA station.

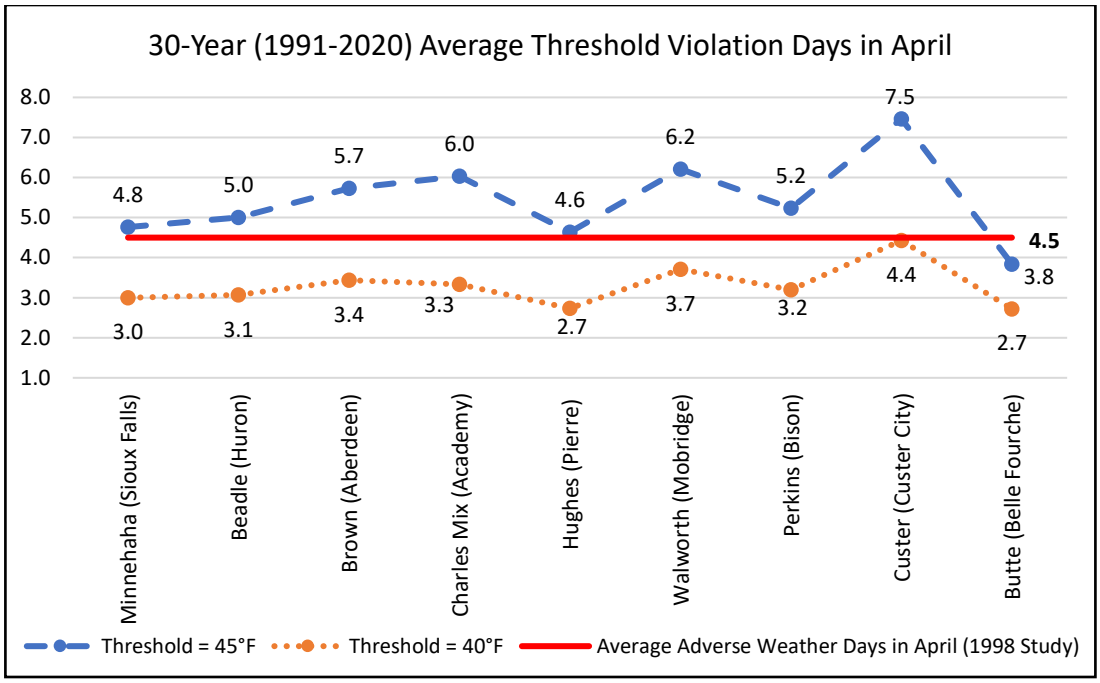


Figure 17. 30-year (1991-2020) average threshold violation days in April by NOAA stations.

Some general observations from Figure 17 include:

- The average number of days with threshold violation decreases when the threshold is reduced from 45°F to 40° F, which is consistent with expectation (i.e., lower temperatures would be met more often).
- The NOAA stations at Custer City and Belle Fourche have the highest and lowest threshold violation days respectively for both thresholds (45°F & 40°F).
- Generally, the threshold violation days are less than the state average when the threshold maximum temperature is 40°F. Only the Custer City NOAA station is close to the state average. The stations at Sioux Falls, Huron, and Bison stations have similar average threshold (40°F) violation days which are located at the South-East, East and North-West parts of South Dakota respectively. Similarly, Aberdeen and Academy stations have similar average threshold (40°F) violation

days which are located at the North-East and South of South Dakota respectively. Additionally, the NOAA stations at Pierre, and Belle Fourche have the lowest average threshold (45°F) violation days (3). They are in the Central and West parts of South Dakota.

- At the 45°F maximum temperature threshold, most of the NOAA stations have a higher number of threshold violation days than the state average, with the only exception being the Belle Fourche station. Belle Fourche has the lowest (3.8) average threshold (45°F) violation days. Custer City station has the highest average threshold (45°F) violation days, which is in the South-West of South Dakota. Huron and Bison stations have similar average threshold (45°F) violation days which are in the East and North-West of South Dakota respectively. The stations at Aberdeen, Academy, and Mobridge have a higher number of days with threshold (45°F) violation.

3.12. Average Threshold Violation Days in April by Year

Within Figure 18 the horizontal line (red, solid) at 4.5 days depicts the expected average number of adverse weather days in April for the State of South Dakota determined by the 1998 study (Kenner et al., 1998). Similar to Figure 17, the upper varying line (blue, dashed) shows the average threshold violation days by year in April at 45°F threshold for each NOAA station. The lower varying line (orange, dotted) shows the average threshold violation days by year in April at 40°F threshold for each NOAA station.

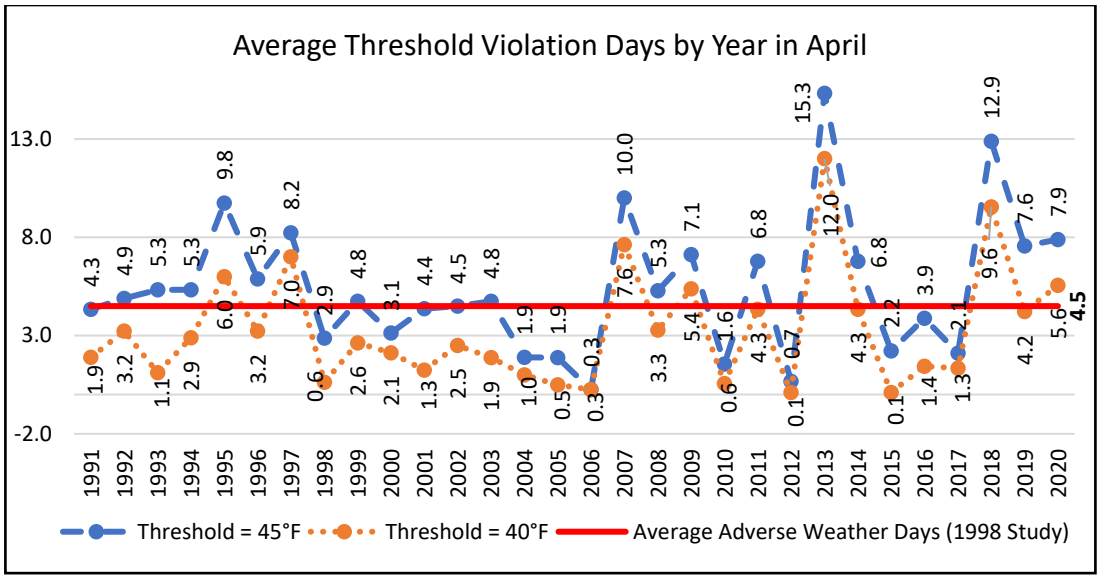


Figure 18. Average threshold violation days in April by year (1991-2020).

Figure 18 shows the average threshold violation days for all NOAA stations located all over South Dakota. Some years (1995, 1997, 2007, 2013, 2018) had noticeably higher threshold violation days than the rest of the years. On the other hand, the threshold violation days were consistently lower from 1998 to 2006. At the 45°F threshold, violation days are generally at or above the 1998 study value (4.5) for the State but when at the 40°F, threshold violation days are generally lower than the 1998 study value.

Within Figure 19 the horizontal line (red, solid) at 4.5 days depicts the expected average number of adverse weather days in April for the State of South Dakota determined by the 1998 study (Kenner et al., 1998). The upper varying line (blue, dashed) shows the 7-year moving average threshold violation days in April at 45°F threshold for each NOAA station. The lower varying line (orange, dotted) shows the 7-year moving average threshold violation days in April at 40°F threshold for each NOAA station.

Again, to remove some of the variability, 7-year moving average values were calculated specific to the month of April, as shown in Figure 19. The moving average decreases during the early period (1997-2006) but then generally trends upward during the more recent years. Also, during the recent years starting from 2013 to 2020, the 7-year moving average values are comparatively higher and are greater than the State average for the 45°F threshold.

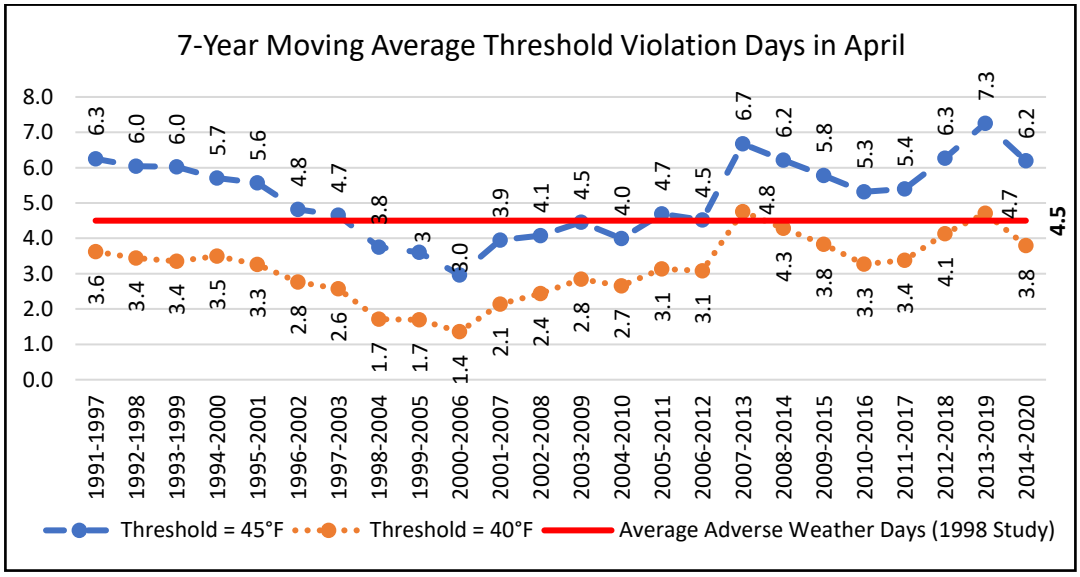
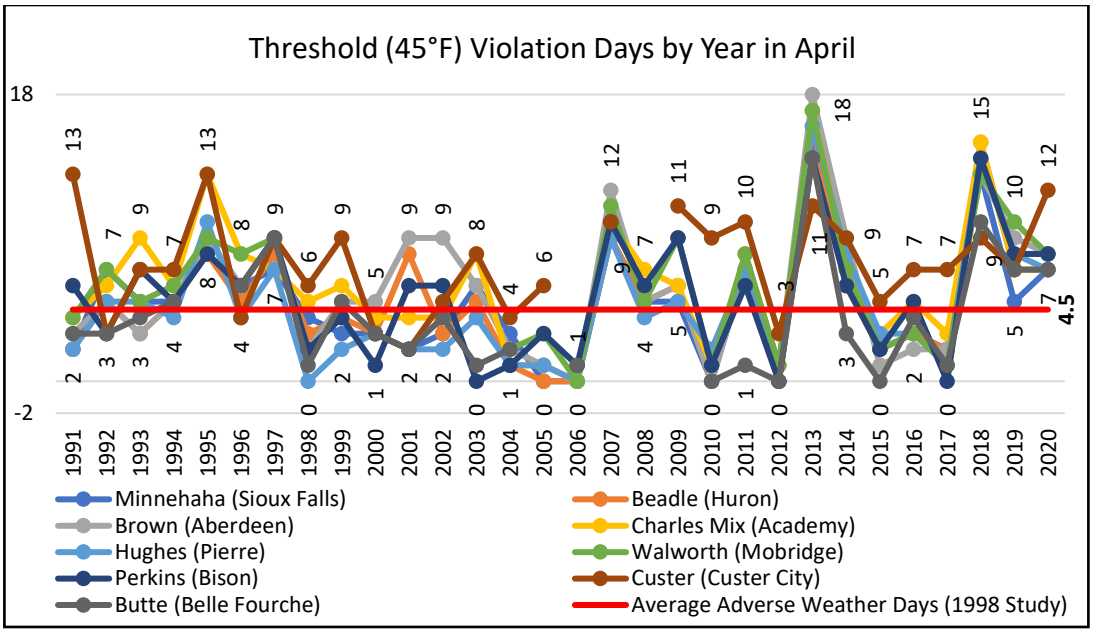


Figure 19. 7-year moving average threshold violation days in April.

3.13. Threshold (45°F) Violation Days by Year in April at NOAA Stations

The number of days that had maximum temperature less than 45°F and 40°F in April from 1991 to 2020 are plotted in Figure 20. The plot does not indicate any noticeable trend over the 30-year (1991-2020) period. Some years (1995, 2007, 2013, 2018) had higher threshold violation days than the rest of the years for all the stations. Note that the Walworth site has missing data from 1998 through 2003; thus, these data points were excluded from the graphs. Overall, the average number of threshold violation days have decreased when the threshold is reduced from 45°F to 40°F as shown in Figure

20. No particular NOAA station has shown the trend of having the highest or lowest threshold violation days. Generally, the stations at Custer City, Aberdeen, and Academy have higher threshold violation days among all the stations. On the other hand, the stations at Bison, Pierre, and Belle Fourche have lower threshold violation days among all the stations.



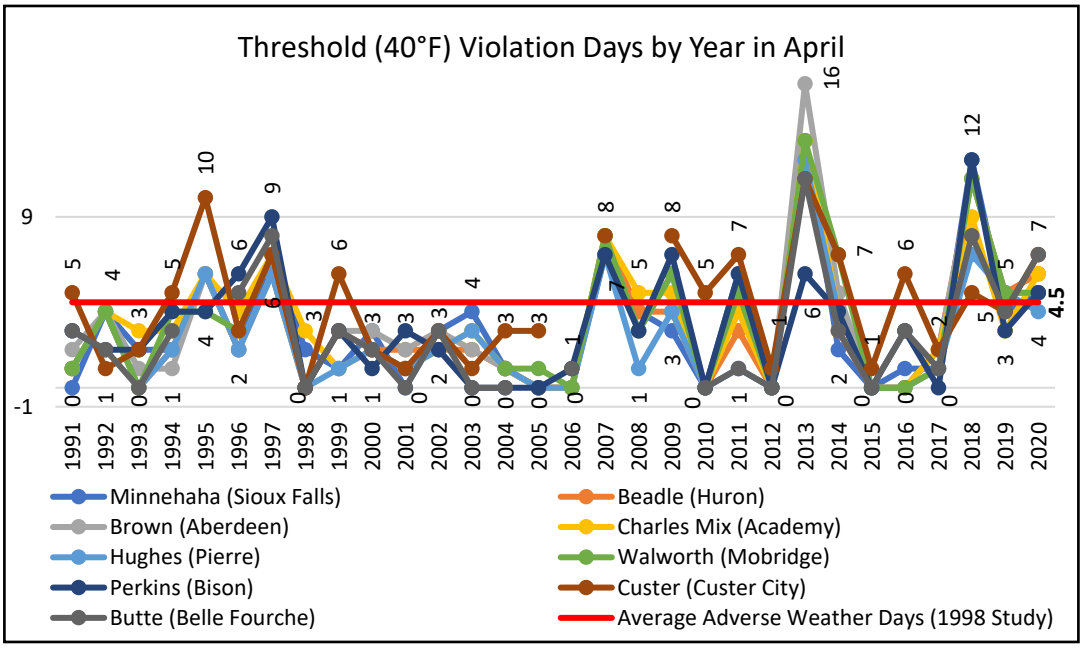


Figure 20. Threshold (45°F and 40°F) violation days in April by year (1991-2020).

3.14. 7-Year Moving Average Threshold (45°F) Violation Days in April

As no apparent trend is displayed in the threshold (45°F) violation days by year for the month of April, a 7-year moving average of the threshold violation days is plotted in Figure 21. It shows the 7-year moving average from 1991 to 2020 for NOAA stations at 9 locations. The horizontal line (red, solid) at 4.5 days depicts the expected average number of adverse weather days in April for the State of South Dakota determined by the 1998 study (Kenner et al., 1998).

The NOAA stations at Custer City and Aberdeen have more threshold (45°F) violation moving average days than the average adverse weather days (4.5) in April for South Dakota for most of the years. On the other hand, the Belle Fourche station has less threshold (45°F) violation moving average days than the State Average (4.5) for most of the years. As Walworth station does not have maximum temperature data from 1998 to 2003, the moving average only shows those timeframes that do not involve that timeframe. Huron and Pierre stations have similar 7-year moving average threshold (45°F) violation days in the recent years (2008-2020). Similarly, Aberdeen and Academy have similar 7-year moving average threshold (45°F) violation days in the recent years (2009-2020). Figure 21 shows a decreasing trend of 7-year moving average threshold (45°F) violation days during the early period (1997-2006) but then generally trends upward during the more recent years.

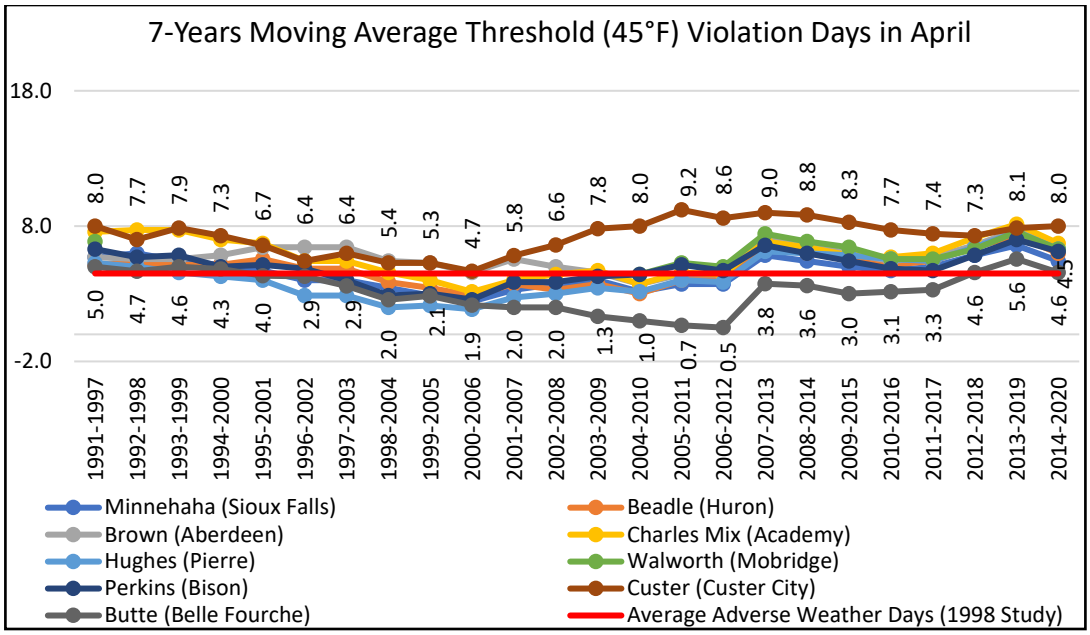


Figure 21. 7-year moving average threshold (45°F) violation days in April.

3.15. 7-Year Moving Average Threshold (40°F) Violation Days in April

As no apparent trend is displayed in the threshold (40°F) violation days by year for the month of April, a 7-year moving average of the threshold violation days is plotted in Figure 22. It shows the 7-year moving average from 1991 to 2020 for NOAA stations at 9 locations. The horizontal line (red, solid) at 4.5 days depicts the expected average number of adverse weather days in April for the State of South Dakota determined by the 1998 study (Kenner et al., 1998).

Generally, all the NOAA stations have 7-year moving average threshold violation days less than the average adverse weather days (4.5) in April for South Dakota, except at Custer City. Custer City consistently had threshold (40°F) violation moving average days greater than the State Average (4.5) from 2009 to 2020. Aberdeen and Mobridge stations have similar 7-year moving average threshold (40°F) violation days in the recent years (2013-2020). Similarly, Academy and Pierre have similar 7-year moving average

threshold (40°F) violation days in the recent years (2015-2020). Figure 22 shows a decreasing trend of 7-year moving average threshold (45°F) violation days during the early period (1997-2006) but then generally trends upward during the more recent years.

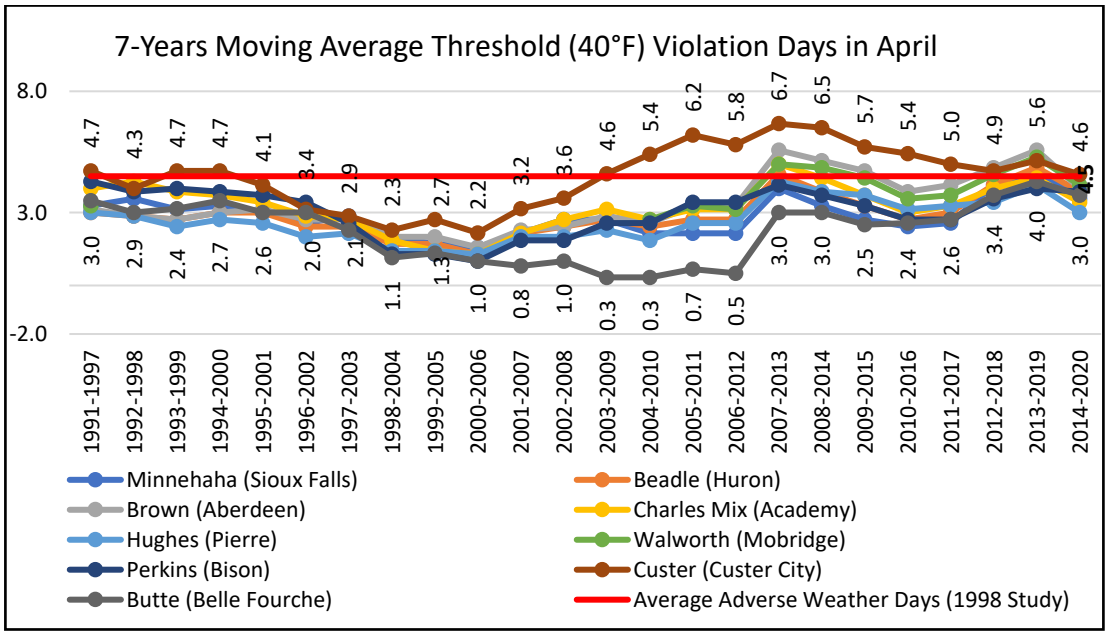


Figure 22. 7-year moving average threshold (40°F) violation days in April.

3.16. 30-Year (1991-2020) Average Threshold Violation Days in October

Within Figure 23 the horizontal line (red, solid) at 3.0 days depicts the expected average number of adverse weather days in October for the State of South Dakota determined by the 1998 study (Kenner et al., 1998). The upper varying line (blue, dashed) shows the average threshold violation days in October at 45°F threshold for each NOAA station. The lower varying line (orange, dotted) shows the average threshold violation days in October at 40°F threshold for each NOAA station.

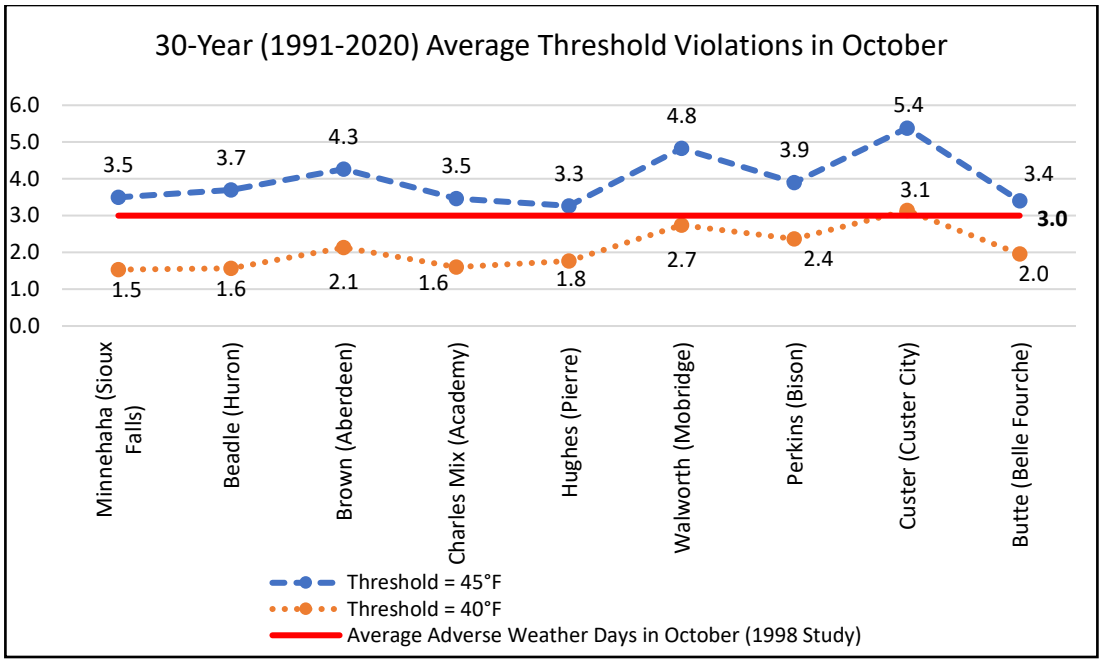


Figure 23. 30-year (1991-2020) average threshold violation days in October by NOAA stations.

Some general observations from Figure 23 include:

- The average number of days with threshold violation decreases when the threshold is reduced from 45°F to 40° F, which is consistent with expectation (i.e., lower temperatures would be met more often).
- The NOAA station at Custer City has the highest threshold violation days for both thresholds (45°F & 40°F).
- Generally, the threshold violation days are less than the state average when the threshold maximum temperature is 40°F. The NOAA stations at Custer City and Mobridge are close to the state average. The stations at Sioux Falls, Huron, and Academy stations have similar average threshold (40°F) violation days which are lower than the rest of the stations. They are in the South-East, East and South of South Dakota respectively.

- At the 45°F maximum temperature threshold, all the NOAA stations have a higher number of threshold violation days than the state average. Custer City station has the highest average threshold (45°F) violation days, which is in the South-West of South Dakota. Sioux Falls and Academy stations have similar average threshold (45°F) violation days which are in the South-East, and South of South Dakota respectively.

3.17. Average Threshold Violation Days in October by Year

Within Figure 24 the horizontal line (red, solid) at 3.0 days depicts the expected average number of adverse weather days in October for the State of South Dakota determined by the 1998 study (Kenner et al., 1998). Similar to Figure 23, the upper varying line (blue, dashed) shows the average threshold violation days by year in October at 45°F threshold for each NOAA station. The lower varying line (orange, dotted) shows the average threshold violation days by year in October at 40°F threshold for each NOAA station.

Figure 24 shows the average threshold violation days for all NOAA stations located all over South Dakota. Some years (2002, 2006, 2009, 2013) had a sudden rise in threshold violation days than the rest of the years. On the other hand, some years (1994, 2004, 2007, 2010, 2014) had a sudden fall in threshold violation days. There has been a gradual increase in the average threshold violation days in the most recent years (2017-2020).

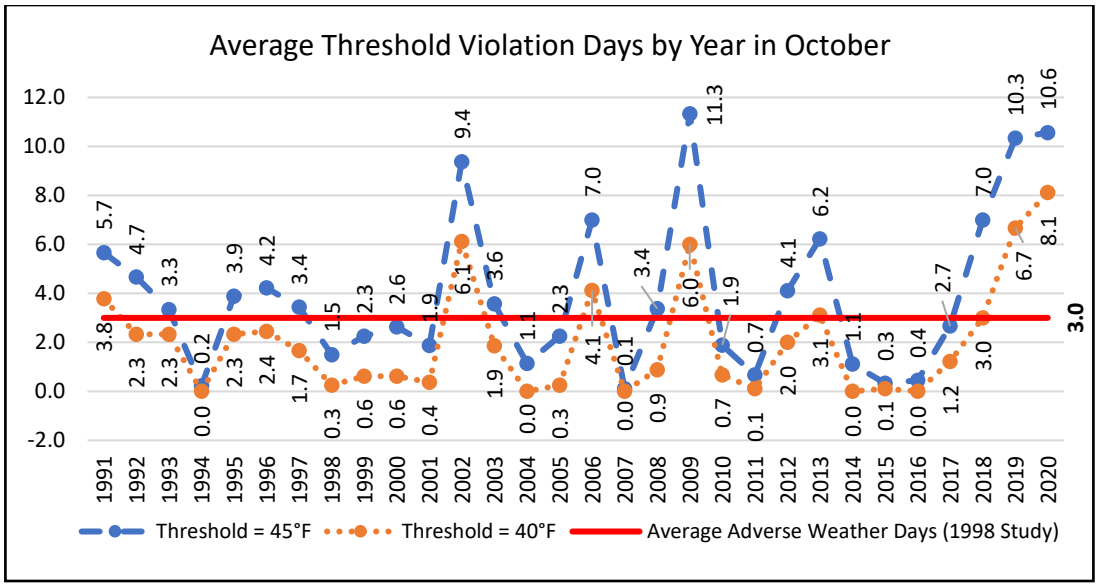


Figure 24. Average threshold violation days in October by year (1991-2020).

Within Figure 25 the horizontal line (red, solid) at 3.0 days depicts the expected average number of adverse weather days in October for South Dakota determined by the 1998 study (Kenner et al., 1998). The upper varying line (blue, dashed) shows the 7-year moving average threshold violation days by year in October at 45°F threshold for each NOAA station. The lower varying line (orange, dotted) shows the 7-year moving average threshold violation days by year in October at 40°F threshold for each NOAA station.

Again, to remove some of the variability, 7-year moving average values were calculated specific to the month of October, as shown in Figure 25. When the threshold is 45°F, most of the moving average values are greater than or equal to the State Average adverse weather days (3.0). On the other hand, when the threshold is reduced to 40°F, all the moving average values are less than the State Average adverse weather days (3). The 7-year moving average threshold violation days show a gradual increase in the recent years (2017-2020).

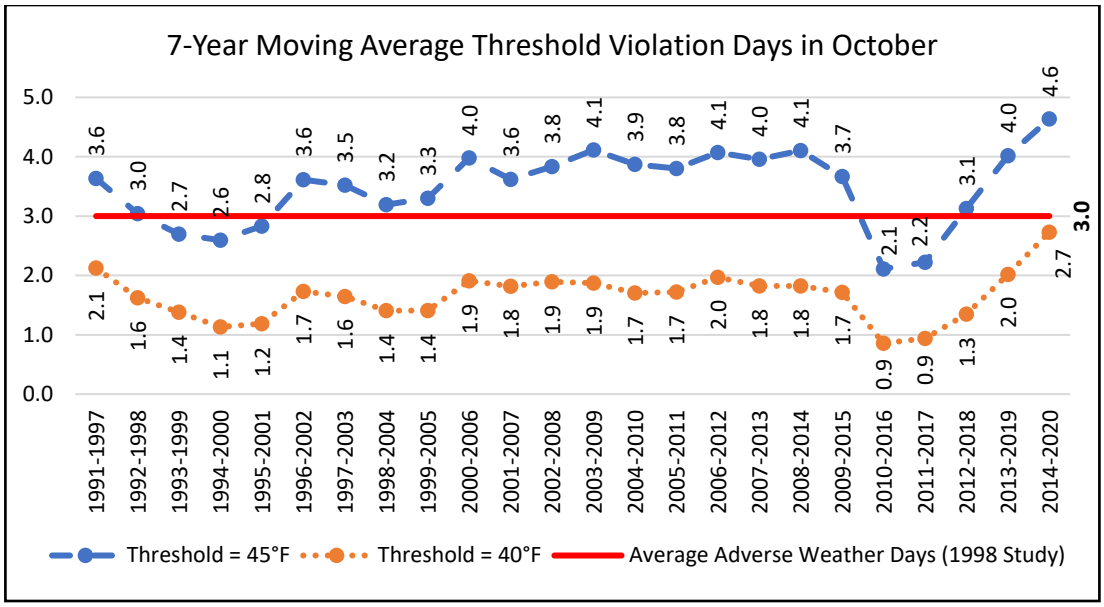


Figure 25. 7-year moving average threshold violation days in October.

3.18. Threshold (45°F) Violation Days by Year in October at NOAA Stations

The number of days that had maximum temperature less than 45°F and 40°F in October from 1991 to 2020 are plotted in Figure 26. The plot does not indicate any noticeable trend over the 30-year (1991-2020) period. Some years (2002, 2006, 2009, 2013, 2019, 2020) had higher threshold violation days than the rest of the years for all the stations. Overall, the average number of threshold violation days have decreased when the threshold is reduced from 45°F to 40° F as shown in Figure 26. Note that the Walworth site has missing data from 1998 through 2003; thus, these data points were excluded from the graphs. No particular NOAA station has shown the trend of having the highest or lowest threshold violation days. Generally, the stations at Custer City, Aberdeen, and Mobridge have higher threshold violation days among all the stations. On the other hand, the Belle Fourche station has lower threshold violation days in the recent years (2010-2020).

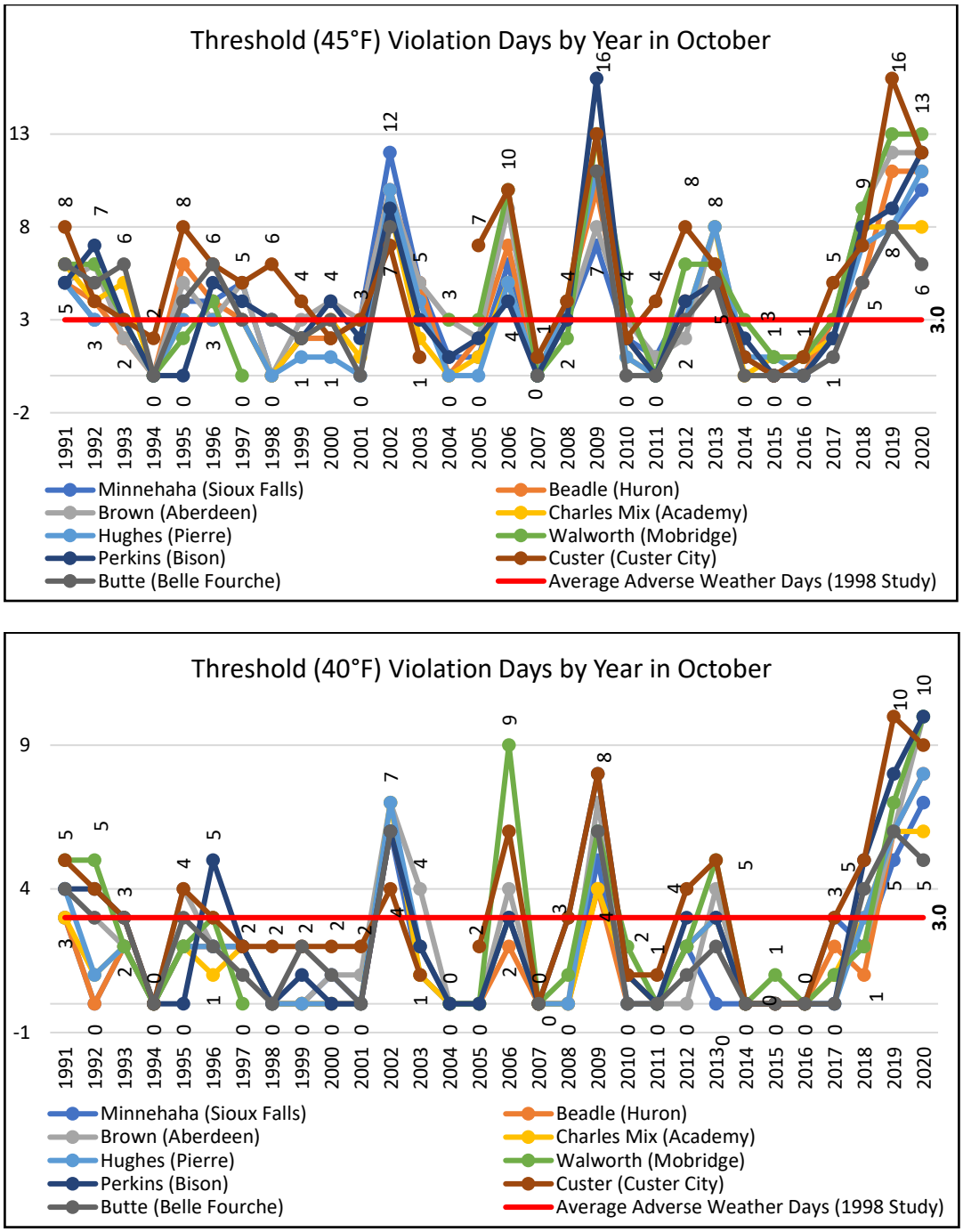


Figure 26. Threshold (45°F and 40°F) violation days in October by year (1991-2020).

3.19. 7-Year Moving Average Threshold (45°F) Violation Days in October

As no apparent trend is displayed in the threshold (45°F) violation days by year for the month of October, a 7-year moving average of the threshold violation days is

plotted in Figure 27. It shows the 7-year moving average from 1991 to 2020 for NOAA stations at 9 locations. The horizontal line (red, solid) at 3.0 days depicts the expected average number of adverse weather days in October for the State of South Dakota determined by the 1998 study (Kenner et al., 1998). Most of the NOAA stations have more threshold (45°F) violation moving average days than the average adverse weather days (3.0) in October for South Dakota from 2006 to 2015. Additionally, the 7-year moving average threshold violation days show a gradual increase in the most recent years (2017-2020).

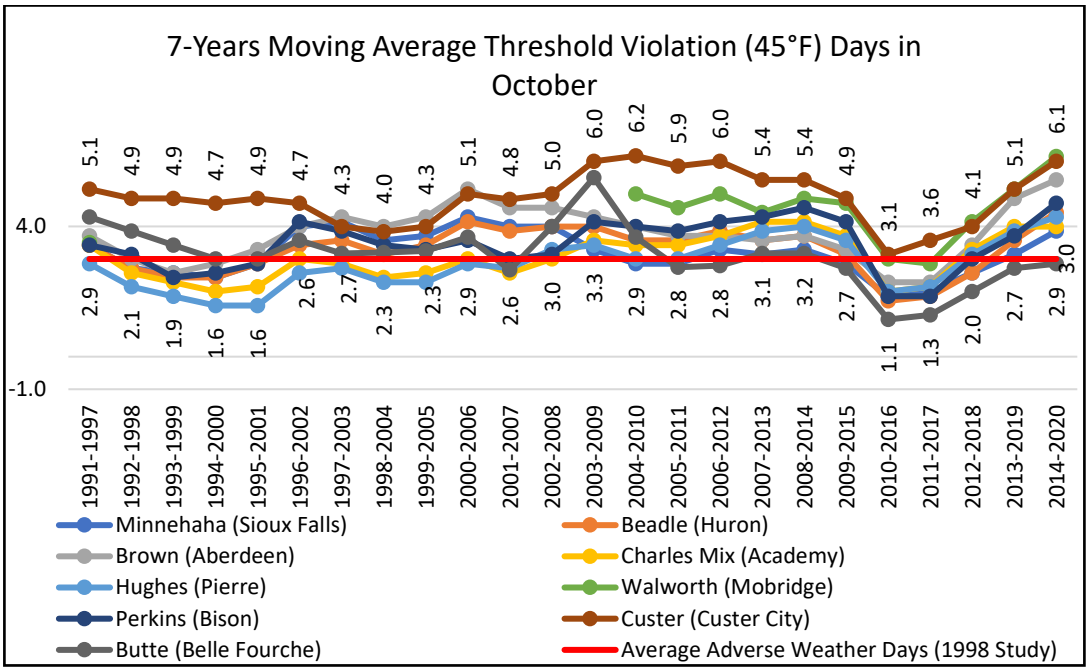


Figure 27. 7-year moving average threshold (45°F) violation days in October.

3.20. 7-Year Moving Average Threshold (40°F) Violation Days in October

As no apparent trend is displayed in the threshold (40°F) violation days by year for the month of October, a 7-year moving average of the threshold violation days is plotted in Figure 28. It shows the 7-year moving average from 1991 to 2020 for NOAA

stations at 9 locations. The horizontal line (red, solid) at 3.0 days depicts the expected average number of adverse weather days in October for the State of South Dakota determined by the 1998 study (Kenner et al., 1998). Generally, all the NOAA stations have 7-year moving average threshold violation days less than the state average adverse weather days (3.0) in October for South Dakota, except some years at Custer City. Additionally, all the stations have experienced a gradual increase in the 7-year moving average threshold violation days in the most recent years (2017-2020).

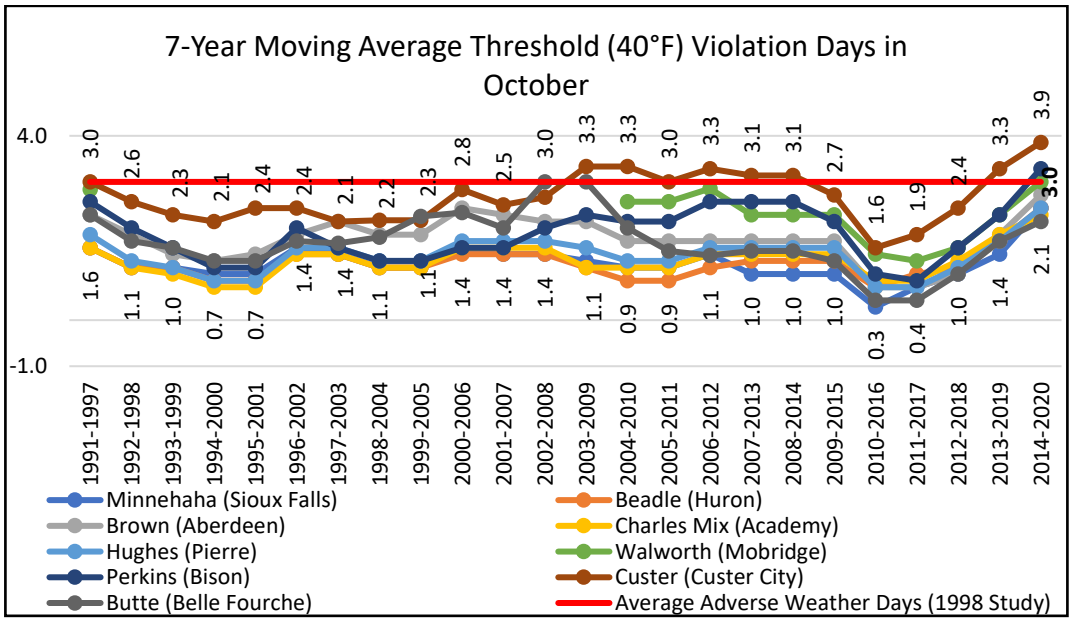


Figure 28. 7-year moving average threshold (40°F) violation days in October.

Since both April and October have less threshold violation days, it would be interesting to do a detailed analysis of threshold violation days for a month that has higher threshold violation days. That is why the detailed analysis of threshold violation days for the month of January is described in the following paragraphs of this chapter.

3.21. 30-Year (1991-2020) Average Threshold Violation Days in January

Within Figure 29 the horizontal line (red, solid) at 18.5 days depicts the expected average number of adverse weather days in January for South Dakota determined by the 1998 study (Kenner et al., 1998). The upper varying line (blue, dashed) shows the average threshold violation days in January at 45°F threshold for each NOAA station. The lower varying line (orange, dotted) shows the average threshold violation days in January at 40°F threshold for each NOAA station. Some general observations from Figure 29 include:

- The average number of days with threshold violation decreases when the threshold is reduced from 45°F to 40° F, which is consistent with expectation (i.e., lower temperatures would be met more often). The 30-year average threshold violation days show a decreasing pattern as the stations move from East to West.
- The NOAA stations at Aberdeen and Belle Fourche have the highest and lowest threshold violation days respectively for both thresholds (45°F & 40°F).
- At the 45°F maximum temperature threshold, all the NOAA stations have higher average threshold violation days than the state average. Generally, the threshold violation days are less than the state average when the threshold maximum temperature is 40°F. The stations at Sioux Falls, Huron, and Mobridge have similar average threshold (both 45°F and 40°F) violation days which are located at the South-East, East and North parts of South Dakota respectively. Similarly, Academy, Pierre, and Bison stations have similar average threshold (both 45°F and 40°F) violation days which are located at the South, Central, and North-West of South Dakota respectively.

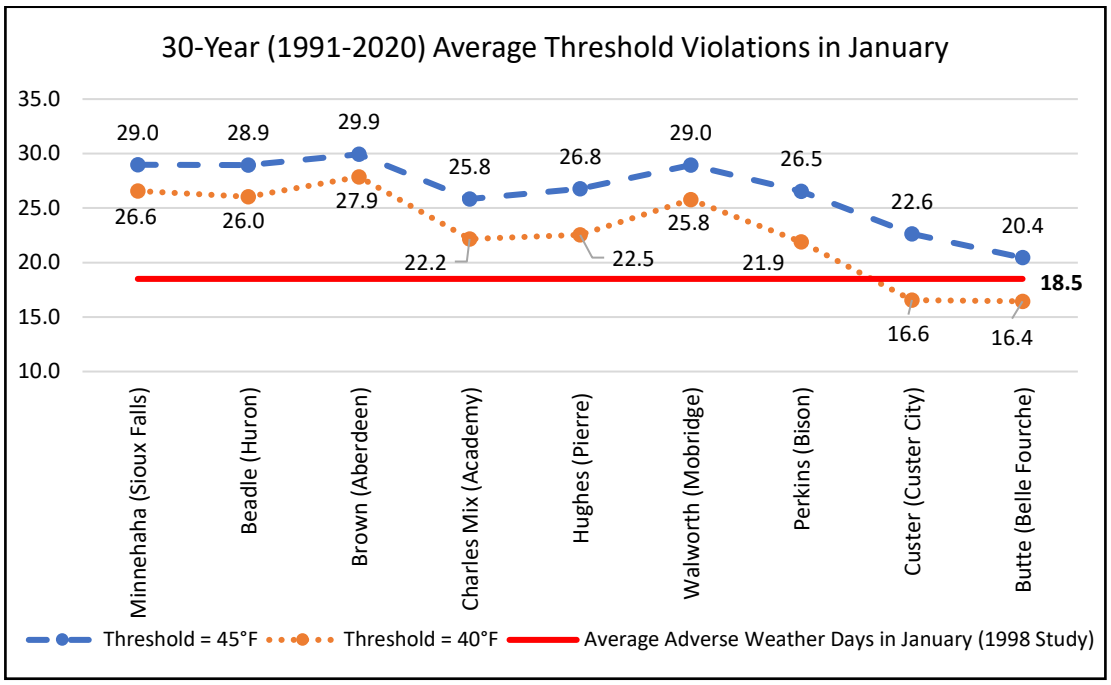


Figure 29. 30-year (1991-2020) average threshold violation days in January by NOAA stations.

3.22. Average Threshold Violation Days in January by Year

Within Figure 30 the horizontal line (red, solid) at 18.5 days depicts the expected average number of adverse weather days in January for South Dakota determined by the 1998 study (Kenner et al., 1998). The upper varying line (blue, dashed) shows the average threshold violation days by year in January at 45°F threshold. The lower varying line (orange, dotted) shows the average threshold violation days by year in January at 40°F threshold.

Figure 30 shows the average threshold violation days in January for all NOAA stations located all over South Dakota. Some years (1992, 2012, 2018) had a sudden fall in threshold violation days than the rest of the years. At the 45°F threshold, the threshold violation days were always above the 1998 study value (18.5) for the State. When the

threshold is reduced to 40°F, the threshold violation days are also generally greater than the 1998 study value except some years (1992, 2002, 2006, 2012, 2015).

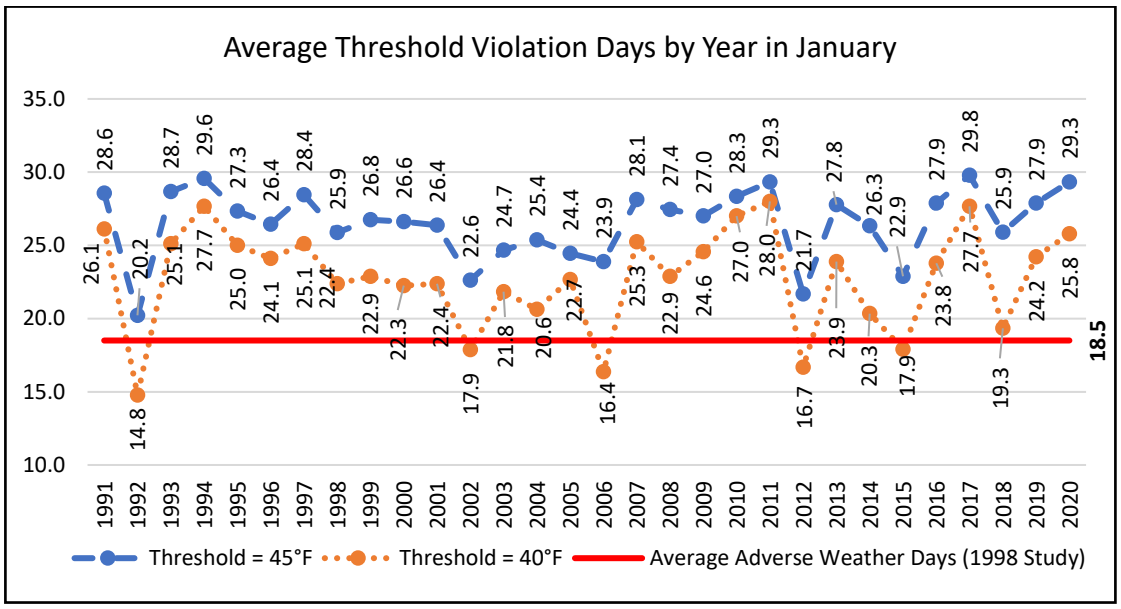


Figure 30. Average threshold violation days in January by year (1991-2020).

Within Figure 31 the horizontal line (red, solid) at 18.5 days depicts the expected average number of adverse weather days in January for the State of South Dakota determined by the 1998 study (Kenner et al., 1998). The upper varying line (blue, dashed) shows the 7-year moving average threshold violation days in January at 45°F threshold. The lower varying line (orange, dotted) shows the 7-year moving average threshold violation days in January at 40°F threshold for each NOAA station.

Again, to remove some of the variability, 7-year moving average values were calculated specific to the month of January, as shown in Figure 31. The 7-year moving average threshold violation days in January are always greater than the state average (18.5) for both thresholds (45°F and 40°F). There seems to have been a decreasing trend for the earlier period (1997-2006) during the 30 years and a generally increasing trend since.

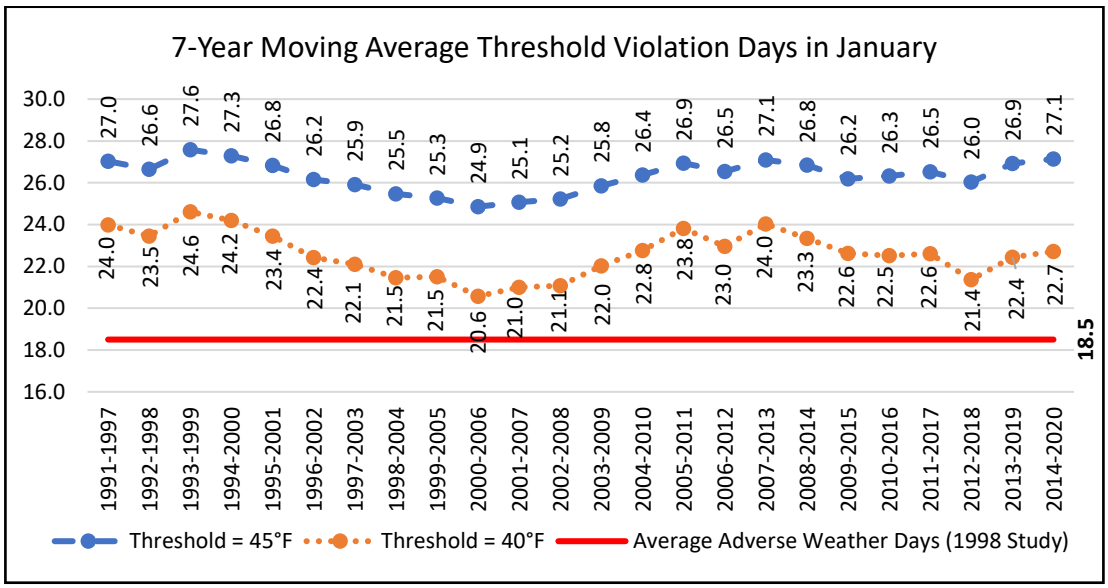


Figure 31. 7-year moving average threshold violation days in January.

3.23. Threshold (45°F) Violation Days by Year in January at NOAA Stations

The number of days that had maximum temperature less than 45°F and 40°F in January from 1991 to 2020 are plotted in Figure 32. The plot does not indicate any noticeable trend over the 30-year (1991-2020) period. Some years (1992, 2012, 2015, 2018) had lower threshold violations than the rest of the years for all the stations. Note that the Walworth site has missing data from 1998 through 2003; thus, these data points were excluded from the graphs. Overall, the average number of threshold violation days have decreased when the threshold is reduced from 45°F to 40° F as shown in Figure 32. In general, the NOAA station at Aberdeen has the highest threshold violations in most of the years compared to other stations. On the other hand, either the Belle Fourche station or Custer City station has the lowest threshold violations in most of the years.

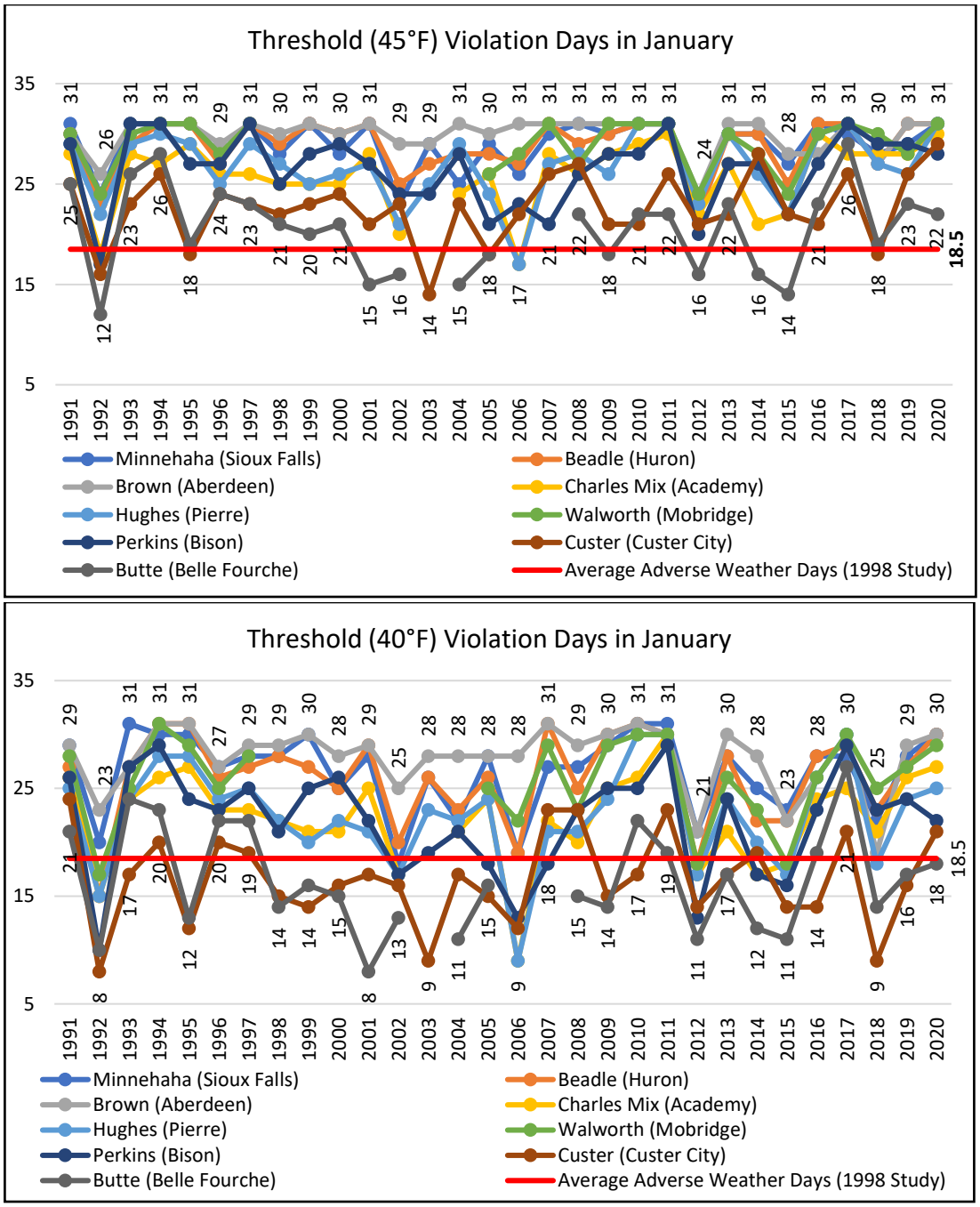


Figure 32. Threshold (45°F & 40°F) violation days in January by year (1991-2020).

3.24. 7-Year Moving Average Threshold (45°F) Violation Days in January

As no apparent trend is displayed in the threshold (45°F) violation days by year for the month of January, a 7-year moving average of the threshold violation days is plotted in Figure 33. It shows the 7-year moving average from 1991 to 2020 for NOAA

stations at 9 locations. The horizontal line (red, solid) at 18.5 days depicts the expected average number of adverse weather days in January for the State of South Dakota determined by the 1998 study (Kenner et al., 1998).

All the NOAA stations except the Belle Fourche station always have more threshold (45°F) violation days than the state average (18.5) over the 30-Year period. The Belle Fourche station also has more threshold (45°F) violation days than the State Average (18.5) in the earlier years (1991-2002) and the recent years (2008-2020). Aberdeen has the highest average threshold (45°F) violation days in January over the 30 years (1991-2020) period. Sioux Falls and Huron have similar average threshold (45°F) violation days for January. Mobridge also has similar average threshold (45°F) violation days in the recent years (2010-2017). They are in the South-East, East, and North of South Dakota. Similarly, the NOAA stations at Academy, Pierre, and Bison have similar average threshold (45°F) violation days for January, which are located at the South, Central and North-West parts of South Dakota.

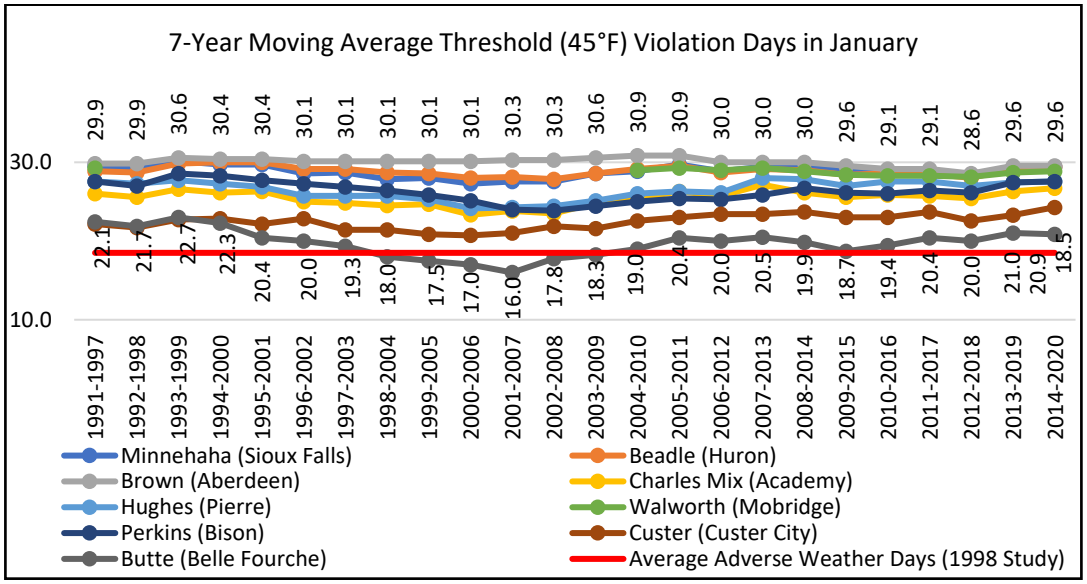


Figure 33. 7-year moving average threshold (45°F) violation days in January.

3.25. 7-Year Moving Average Threshold (40°F) Violation Days in January

Figure 34 shows the 7-year moving average from 1991 to 2020 for NOAA stations at 9 locations. The horizontal line (red, solid) at 18.5 days depicts the expected average number of adverse weather days in January for the State of South Dakota determined by the 1998 study (Kenner et al., 1998).

Except for Belle Fourche and Custer City stations, all the NOAA stations generally have more threshold (40°F) violation days than the state average (18.5) over the 30-Year period. Aberdeen has the highest average threshold (40°F) violation days in January over the 30 years (1991-2020) period. Sioux Falls and Huron have similar average threshold (40°F) violation days for January. Mobridge also has similar average threshold (40°F) violation days in the recent years (2010-2017). They are in the South-East, East, and North of South Dakota. Similarly, the NOAA stations at Academy, Pierre, and Bison have similar average threshold (40°F) violation days for January, which are located at the South, Central and North-West parts of South Dakota.

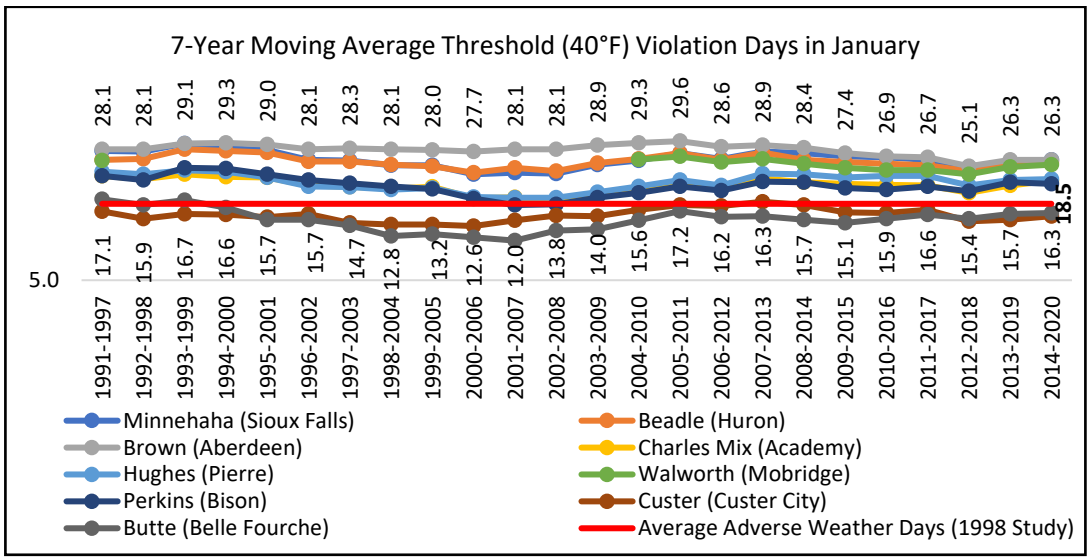


Figure 34. 7-year moving average threshold (40°F) violation days in January.

3.26. Comparative Analysis between Weekly Progress Report (WPR) and NOAA Data

Based on the Weekly Progress Report (WPR) provided by the South Dakota Department of Transportation (SDDOT), the project sites were selected to spatially represent South Dakota. Within this comparative analysis, the maximum temperature data from WPRs were compared with the nearest NOAA stations located in the same county.

Table 26 and Figure 35 display the percentage of WPR data and NOAA data match, where data match for this table is defined by exact match without any tolerance. Only the project site at Minnehaha County has a very high (98.3%) percentage of maximum temperature data match with the NOAA station at Sioux Falls. Two other project sites at Brown and Beadle counties have moderate data match with the proximal NOAA stations at Aberdeen and Huron, respectively. The remaining project sites exhibit a low percentage of data to match with the corresponding NOAA stations.

Table 26. Percentage of WPR and NOAA data match by project sites.

Location of Project Sites	Total Data	Data Exact Match		Data Don't Match	
		Number	Percentage	Number	Percentage
Minnehaha (Sioux Falls)	289	284	98.3%	5	1.7%
Beadle (Huron)	540	207	38.3%	333	61.7%
Brown (Aberdeen)	268	147	54.9%	121	45.1%
Spink (Redfield)	230	10	4.3%	220	95.7%
Charles Mix (Academy)	187	5	2.7%	182	97.3%
Walworth (Mobridge)	119	21	17.6%	98	82.4%
Perkins (Bison)	195	16	8.2%	179	91.8%
Custer (Custer City)	85	4	4.7%	81	95.3%
Butte (Belle Fourche)	96	7	7.3%	89	92.7%

The distance between the project site and the NOAA station may be a factor that might cause the mismatch of maximum temperature data between WPR and NOAA data. Distance, in this case, is defined by the straight-line distance between the NOAA station point and the midpoint of the project site, whether linear or point. Table 27 shows the maximum temperature data match percentage between project site and the corresponding NOAA station distance between project sites and NOAA stations. Included in this table the percentage of data match at different tolerance limits (±1°F, ±2°F, ±3°F, ±4°F, ±5°F) as opposed to solely exact match.

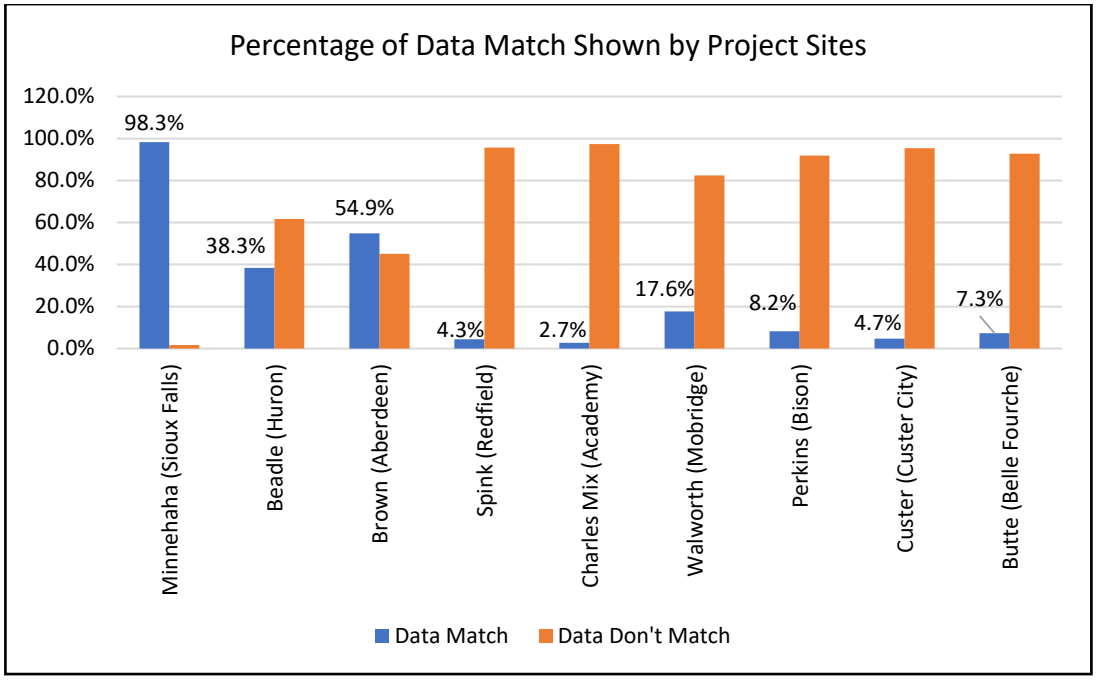


Figure 35. Percentage of WPR and NOAA data match by project sites.

Figure 36 depicts this information graphically. The Minnehaha project site has the highest percentage of data match at all tolerance limits and does not increase much as the tolerance is increased. The Brown and Beadle project sites percentages improve as tolerance limits are widened. The percentages for these two sites increase markedly over the tolerance limits, both exceeding 90% at the highest tolerance limit. The Walworth

site, though it displays a low exact match, also exceeds 90% match at the highest tolerance limit. Three additional sites (Butte, Perkins, and Custer) get near or exceed 70% at the highest tolerance limit while the Charles Mix site never exceeds 40%. Largely, the distances do not appear to impact the results, but the argument could certainly be made for the Charles Mix site that proximity, particularly given the topography, likely factors in.

Table 27. Data match between WPR project sites and NOAA stations with distance.

Project Site (City of NOAA Station)	Distance between WPR & NOAA (miles)	Exact Data Match	Percentage of Data Match at				
			tolerance = ±1°F	tolerance = ±2°F	tolerance = ±3°F	tolerance = ±4°F	tolerance = ±5°F
Brown (Aberdeen)	1.5	54.9%	67.9%	81.7%	87.7%	91.8%	94.4%
Butte (Belle Fourche)	12.2	7.3%	18.8%	35.4%	56.3%	67.7%	76.0%
Perkins (Bison)	14.6	8.2%	24.6%	35.4%	48.7%	60.5%	69.7%
Beadle (Huron)	17.2	38.3%	69.6%	79.3%	84.1%	88.1%	90.7%
Custer (Custer City)	17.7	4.7%	20.0%	37.6%	51.8%	58.8%	70.6%
Spink (Redfield)	22.5	4.3%	12.2%	22.2%	29.1%	38.3%	44.8%
Minnehaha (Sioux Falls)	23.4	98.3%	99.0%	99.0%	99.7%	99.7%	99.7%
Walworth (Mobridge)	47.5	17.6%	42.9%	63.9%	75.6%	87.4%	92.4%
Charles Mix (Academy)	61.4	2.7%	8.0%	16.6%	25.1%	31.0%	36.4%

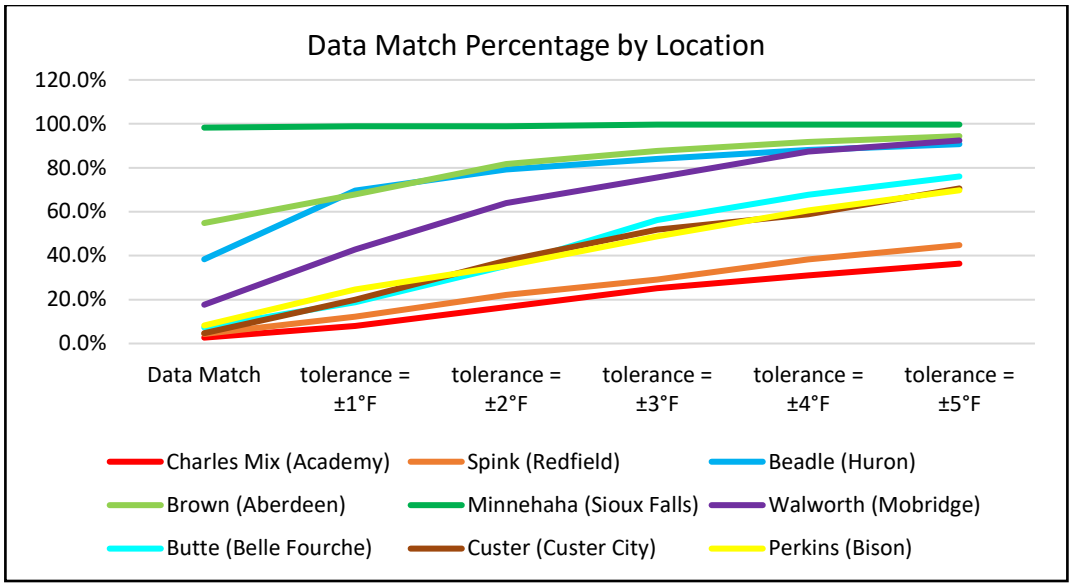


Figure 36. Percentage of data match between WPR project sites and NOAA stations.

CHAPTER 4: RESULTS AND DISCUSSION

The Analysis section discussed the yearly and monthly aspects of threshold (both 40°F and 45°F) violation days over 30-Year (1991-2020) period, and these violation days are compared to the expected adverse weather days found from the 1998 study (Kenner et al., 1998). Moreover, it is also analyzed if the maximum temperature data matches the weekly progress report (WPR) data for project sites and their corresponding NOAA stations' data. The Results & Discussion section focuses on the findings of the analysis and explains how they are connected to the thesis objectives.

4.1. Average Annual Threshold Violation Days

Table 28 shows the 30-year (1991-2020) average threshold violation days for threshold maximum temperature of 45°F and 40°F. The average number of days with threshold violation decreases when the threshold is reduced from 45°F to 40° F, which is consistent with expectation (i.e., lower temperatures would be met more often). The 30-Year (1991-2020) average threshold violation days are always higher at 45°F than 40°F. The average threshold violation days per year for 45°F and 40°F are 109.7 and 87.5 respectively. So, there is an average difference of 22.2 days per year in threshold violation days between 45°F and 40°F. The NOAA station at Aberdeen has the highest average threshold violation days (131.5 for 45°F, 111.0 for 40°F). On the other hand, the NOAA station at Belle Fourche has the lowest average threshold violation days (79.3 for 45°F, 59.3 for 40°F).

Table 28. 30-year (1991-2020) average threshold violation days per year.

Sl.	Station ID	Station Name	30-Year (1991-2020) Average Threshold Violation Days		
			Threshold = 45°F	Threshold = 40°F	Difference
1	USW00014944	SIOUX FALLS FOSS FIELD, SD US	120.4	99.8	20.7
2	USW00014936	HURON REGIONAL AIRPORT, SD US	120.9	100.4	20.4
3	USW00014929	ABERDEEN REGIONAL AIRPORT, SD US	131.5	111.0	20.5
4	USC00390043	ACADEMY 2 NE, SD US	108.5	86.2	22.3
5	USW00024025	PIERRE REGIONAL AIRPORT, SD US	110.7	87.2	23.5
6	USC00395691	MOBRIDGE 2 NNW, SD US	98.7	81.3	17.4
7	USC00390701	BISON, SD US	112.6	88.8	23.8
8	USC00392087	CUSTER, SD US	104.9	73.9	30.9
9	USC00390559	BELLE FOURCHE, SD US	79.3	59.3	20.0
		Average =	109.7	87.5	22.2

The year-by-year average threshold violation days plot does not show any particular trend. Some years (1999, 2012, 2015) had a sudden decrease in average annual threshold violation days than the rest of the years. On the other hand, some years (2013, 2018) had a sudden increase in average threshold violation days. Generally, the NOAA station at Aberdeen has the highest threshold violation days in most of the years among all the stations. On the other hand, the Belle Fourche station generally has the lowest threshold violations in most of the years. This is true for both thresholds (45°F and 40°F).

The average number of days with threshold violation decreases when the threshold is reduced from 45°F to 40° F. The 7-year moving average plot shows that when threshold is 45°F, most of the moving average values are generally greater than the State average adverse weather days (101.3). But when threshold is reduced to 40°F, the moving average values are always less than the State average adverse weather days (101.3). There seems to have been a decreasing trend for the earlier period (1997-2006) during the 30 years and a generally increasing trend since.

When threshold is 45°F, all the NOAA stations have more 7-year moving average threshold (45°F) violation days than the State average (101.3) for South Dakota, except the Belle Fourche station. The stations at Huron and Sioux Falls have similar 7-year moving average annual threshold (45°F) violation days. Additionally, the NOAA stations at Academy and Custer City have similar moving average annual threshold (45°F) violation days in the recent years (1998-2020). Similarly, the NOAA stations at Pierre and Bison have similar moving average annual threshold (45°F) violation days in the recent years (1998-2020).

When threshold is 40°F, all the NOAA stations have less 7-year moving average threshold (45°F) violation days than the State average (101.3) for South Dakota, except the Aberdeen station. The stations at Huron and Sioux Falls have similar moving average threshold (40°F) violation days per year. Similarly, the NOAA stations at Academy, Pierre, and Bison have similar moving average threshold (40°F) violation days over the 30-Year period.

4.2. Average Threshold Violation Days by Month

Temperature does not have much effect on causing adverse weather day for the months of May, June, July, August, and September. May has the lowest average threshold violation days at all 9 locations, April and October have similar, slightly higher averages, March and November are similar and, again, somewhat higher, with February and December still higher, and January the highest.

The 30-year average threshold violation days show a decreasing pattern as the stations move from East to West. The violation days are similar for all months at the Sioux Falls, Huron, Aberdeen, and Mobridge stations. They are in the East and North South Dakota. Similarly, the Academy, Pierre, and Bison stations have similar average threshold violation days across all months. Academy is in Southern part, Pierre is in Central part, and Bison is in North-West part of South Dakota. The Belle Fourche station located in the West of South Dakota has the lowest average threshold violation days for all months.

It is found from the Standard Specifications for Roads and Bridges for the State of South Dakota (South Dakota DOT, 2015) that the seasonal limitation for surfacing works is from May 1 to October 15 (inclusive). So, April is the transition month for starting the work and October is the transition month for stopping the work. A more detailed analysis for the months of April and October can provide more information about the threshold violation days at different locations of South Dakota.

4.2.1. Average Threshold Violation Days in April

The 30-Year (1991-2020) average threshold violation days for the month of April are always higher at 45°F than 40°F as shown in Table 29. The average threshold violation days per year for 45°F and 40°F are 5.4 and 3.3 respectively. So, there is an average difference of 2.1 days in threshold violation days between 45°F and 40°F for the month of April.

Table 29. 30-year (1991-2020) average threshold violation days in April.

Sl.	Station ID	Station Name	30-Year (1991-2020) Average Threshold Violation Days in April		
			Threshold = 45°F	Threshold = 40°F	Difference
1	USW00014944	SIOUX FALLS FOSS FIELD, SD US	4.8	3.0	1.8
2	USW00014936	HURON REGIONAL AIRPORT, SD US	5.0	3.1	1.9
3	USW00014929	ABERDEEN REGIONAL AIRPORT, SD US	5.7	3.4	2.3
4	USC00390043	ACADEMY 2 NE, SD US	6.0	3.3	2.7
5	USW00024025	PIERRE REGIONAL AIRPORT, SD US	4.6	2.7	1.9
6	USC00395691	MOBRIDGE 2 NNW, SD US	6.2	3.7	2.5
7	USC00390701	BISON, SD US	5.2	3.2	2.0
8	USC00392087	CUSTER, SD US	7.5	4.4	3.0
9	USC00390559	BELLE FOURCHE, SD US	3.8	2.7	1.1
		Average =	5.4	3.3	2.1

The average number of days with threshold violation decreases when the threshold is reduced from 45°F to 40° F. The average number of adverse weather days in April is 4.5 for the state of South Dakota as per the previous study conducted in 1998 (Kenner et al., 1998). When the threshold maximum temperature is 45°F, the average

number of threshold violation days are greater than the average number of adverse weather days (4.5) in April for all the stations except the Belle Fourche station. But when the threshold maximum temperature is reduced to 40°F, the average number of threshold violation days is always less than the average number of adverse weather days for all the stations. Overall, the NOAA stations at Custer City and Belle Fourche have the highest and lowest 30-year average threshold violation days respectively for both thresholds (45°F & 40°F).

The year-by-year average threshold violation days plot does not show any particular trend. Some years (1995, 1997, 2007, 2013, 2018) had a sudden rise in threshold violation days. On the other hand, the threshold violation days have been consistently lower from 1998 to 2006 than the rest of the years. Generally, the stations at Custer City, Aberdeen, and Academy have higher threshold violation days among all the stations. On the other hand, the stations at Bison, Pierre, and Belle Fourche have lower threshold violation days among all the stations. The 7-year moving average threshold (both 45°F and 40°F) violation days decrease during the early period (1997-2006) but then generally trends upward during the more recent years.

At 45°F maximum temperature threshold, Huron and Pierre have similar 7-year moving average threshold (45°F) violation days in the recent years (2008-2020). Similarly, Aberdeen and Academy have similar 7-year moving average threshold (45°F) violation days in the recent years (2009-2020). On the other hand, at 40°F threshold, Aberdeen and Mobridge stations have similar 7-year moving average threshold (40°F) violation days in the recent years (2013-2020). Similarly, Academy and Pierre have

similar 7-year moving average threshold (40°F) violation days in the recent years (2015-2020).

4.2.2. Average Threshold Violation Days in October

The 30-Year (1991-2020) average threshold violation days in October are always higher at 45°F than 40°F as shown in Table 30. The average threshold violation days per year for 45°F and 40°F are 4.0 and 2.1 respectively. So, there is an average difference of 1.9 days in threshold violation days between 45°F and 40°F for the month of October.

Table 30. 30-year (1991-2020) average threshold violation (TV) days in October.

Sl.	Station ID	Station Name	30-Year (1991-2020) Average TV Days in October		
			Threshold = 45°F	Threshold = 40°F	Difference
1	USW00014944	SIOUX FALLS FOSS FIELD, SD US	3.5	1.5	2.0
2	USW00014936	HURON REGIONAL AIRPORT, SD US	3.7	1.6	2.1
3	USW00014929	ABERDEEN REGIONAL AIRPORT, SD US	4.3	2.1	2.1
4	USC00390043	ACADEMY 2 NE, SD US	3.5	1.6	1.9
5	USW00024025	PIERRE REGIONAL AIRPORT, SD US	3.3	1.8	1.5
6	USC00395691	MOBRIDGE 2 NNW, SD US	4.8	2.7	2.1
7	USC00390701	BISON, SD US	3.9	2.4	1.5
8	USC00392087	CUSTER, SD US	5.4	3.1	2.2
9	USC00390559	BELLE FOURCHE, SD US	3.4	2.0	1.4
		Average =	4.0	2.1	1.9

The average number of days with threshold violation decreases when the threshold is reduced from 45°F to 40° F. The average number of adverse weather days in October is 3.0 for South Dakota as per the previous study conducted in 1998 (Kenner et

al., 1998). When the threshold maximum temperature is 45°F, the average number of threshold violation days are always greater than the average number of adverse weather days (3.0) in October for all the stations. But when the threshold maximum temperature is reduced to 40°F, the average threshold violation days are generally less than the state average (3.0). Custer City station has the highest threshold violation days for both the thresholds (45°F & 40°F).

The year-by-year average threshold violation days plot does not show any particular trend. Some years (2002, 2006, 2009, 2013) had a sudden rise in threshold violation days than the rest of the years. On the other hand, some years (1994, 2004, 2007, 2010, 2014) had a sudden fall in threshold violation days. No particular NOAA station has shown the trend of having the highest or lowest threshold violation days. Generally, the stations at Custer City, Aberdeen, and Mobridge have higher threshold violation days among all the stations. On the other hand, the Belle Fourche station has lower threshold violation days in the recent years (2010-2020).

When threshold is 45°F, most of the NOAA stations have more threshold (45°F) violation moving average days than the average adverse weather days (3.0) in October for South Dakota from 2006 to 2015. However, apart from a few years at Custer City, the NOAA stations generally have the moving average threshold violation days lower than the state average (3.0) for the 40°F threshold. Additionally, the 7-year moving average threshold (both 45°F and 40°F) violation days show a gradual increase in the most recent years (2017-2020).

A detailed analysis was conducted in the analysis for the month of January which has higher threshold violation days among all the months.

4.2.3. Average Threshold Violation Days in January

The 30-Year (1991-2020) average threshold violation days for the month of January are always higher at 45°F than 40°F as shown in Table 31. The average threshold violation days per year for 45°F and 40°F are 26.6 and 22.9 respectively. So, there is an average difference of 3.7 days in threshold violation days between 45°F and 40°F for the month of January.

Table 31. 30-year (1991-2020) average threshold violation (TV) days in January.

Sl.	Station ID	Station Name	30-Year (1991-2020) Average TV Days in January		
			Threshold = 45°F	Threshold = 40°F	Difference
1	USW00014944	SIOUX FALLS FOSS FIELD, SD US	29.0	26.6	1.8
2	USW00014936	HURON REGIONAL AIRPORT, SD US	28.9	26.0	1.9
3	USW00014929	ABERDEEN REGIONAL AIRPORT, SD US	29.9	27.9	2.3
4	USC00390043	ACADEMY 2 NE, SD US	25.8	22.2	2.7
5	USW00024025	PIERRE REGIONAL AIRPORT, SD US	26.8	22.5	1.9
6	USC00395691	MOBRIDGE 2 NNW, SD US	29.0	25.8	2.5
7	USC00390701	BISON, SD US	26.5	21.9	2.0
8	USC00392087	CUSTER, SD US	22.6	16.6	3.0
9	USC00390559	BELLE FOURCHE, SD US	20.4	16.4	1.1
		Average =	26.6	22.9	3.7

The average number of days with threshold violation decreases when the threshold is reduced from 45°F to 40° F. The average number of adverse weather days in

January is 18.5 for South Dakota as per the previous study conducted in 1998 (Kenner et al., 1998). When the threshold maximum temperature is 45°F, the average number of threshold violation days are always greater than the average adverse weather days (18.5) in January for all the stations. Generally, the threshold violation days are less than the state average when the threshold maximum temperature is 40°F. Overall, the NOAA stations at Aberdeen and Belle Fourche have the highest and lowest threshold violation days respectively for both the thresholds (45°F & 40°F).

The year-by-year average threshold violation days plot does not show any particular trend. Some years (1992, 2012, 2018) had a sudden fall in threshold violation days than the rest of the years. The 7-year moving average threshold violation days decrease during the early period (1997-2006) but a generally increasing trend since. Generally, the NOAA station at Aberdeen has the highest threshold violations in most of the years compared to other stations. On the other hand, either the Belle Fourche station or Custer City station has the lowest threshold violations in most of the years.

Sioux Falls and Huron have similar average threshold (both 45°F and 40°F) violation days for January. Mobridge also has similar average threshold (both 45°F and 40°F) violation days in the recent years (2010-2017). Similarly, the NOAA stations at Academy, Pierre, and Bison have similar average threshold (both 45°F and 40°F) violation days.

4.3. Comparison of WPR vs. NOAA Data

Only the project site at Minnehaha County has a very high (98.3%) percentage of maximum temperature data match with the NOAA station at Sioux Falls. The other two project sites at Brown and Beadle counties have moderate percentage of data match with

the NOAA stations at Aberdeen and Huron respectively. They have 54.9% and 38.3% of data match respectively. The other project sites show a low percentage of maximum temperature data match with the corresponding NOAA stations.

As expected, the percentage of data match increases with the increase in tolerance limit (±1°F, ±2°F, ±3°F, ±4°F, ±5°F). The Brown and Beadle project sites' percentages improve as tolerance limits are widened, both exceeding 90% at the highest tolerance limit. The Walworth site also exceeds 90% match at the highest tolerance limit. Three additional sites (Butte, Perkins, and Custer) get near or exceed 70% at the highest tolerance limit while the Charles Mix site never exceeds 40%.

The distance between project sites and the corresponding NOAA stations are considered in the analysis. It is apparent that that there is no direct relationship between the data match percentage, and the distance of project site and NOAA station.

4.4. Conclusions

This chapter discussed the findings of the analysis based on their relevance to the thesis objectives. The first objective of the thesis is to determine if the number of adverse weather days increased in the last 30 years (1991-2020) compared to the value reported in the 1998 SD DOT study. It is done for both annually and monthly (January, April, October). The observations from the analysis are listed below:

- The average number of days with threshold violation decreases in all the cases (annually and monthly) when the threshold is reduced from 45°F to 40° F, which is consistent with expectation (i.e., lower temperatures would be met more often). When threshold is 45°F, all the NOAA stations have more 7-year moving average annual

threshold (45°F) violation days than the State average (101.3) for South Dakota, except the Belle Fourche station. On the other hand, when threshold is 40°F, all the NOAA stations have less 7-year moving average annual threshold (45°F) violation days than the State average (101.3) for South Dakota, except the Aberdeen station.

- Generally, the NOAA station at Aberdeen has the highest average annual threshold violation days in most of the years among all the stations. These days gradually decrease as the NOAA stations move from East to West. Eventually, the Belle Fourche station generally has the lowest average annual threshold violation days in most of the years. This is true for both thresholds (45°F and 40°F).
- There seems to have been a decreasing trend of 7-year moving average annual threshold violation days for the earlier period (1997-2006) during the 30 years and a generally increasing trend since.
- For the month of April, when the threshold is 45°F, the average threshold violation days are greater than the average adverse weather days (4.5) in April for all the stations except the Belle Fourche station. But when the threshold maximum temperature is reduced to 40°F, the average threshold violation days is always less than the average adverse weather days for all the stations. The NOAA stations at Custer City and Belle Fourche have the highest and lowest 30-year average threshold violation days respectively for both the thresholds (45°F & 40°F) in April. The 7-year moving average threshold (both 45°F and 40°F) violation days decrease during the early period (1997-2006) but then generally trends upward during the more recent years for the month of April.

- In October, when the threshold is 45°F, the average threshold violation days are always greater than the average adverse weather days (3.0) in October for all the stations. But when the threshold is reduced to 40°F, the average threshold violation days are generally less than the state average (3.0). Custer City station has the highest 30-year average threshold violation days for both the thresholds (45°F & 40°F). The 7-year moving average threshold (both 45°F and 40°F) violation days show a gradual increase in the most recent years (2017-2020).
- In January, when the threshold is 45°F, the average threshold violation days are always greater than the average adverse weather days (18.5) in January for all the stations. Generally, the threshold violation days are less than the state average when the threshold is 40°F. The NOAA stations at Aberdeen and Belle Fourche have the highest and lowest 30-year average threshold violation days respectively for both the thresholds (45°F & 40°F). The 7-year moving average threshold violation days decrease during the early period (1997-2006) but a generally increasing trend since.

Another objective of the thesis is to determine if the maximum temperature data of the closest weather stations matches the weekly progress report (WPR) data for a subset of project sites. The observations from the analysis are listed below:

- The project site at Minnehaha County has a very high (98.3%) percentage of maximum temperature data match with the corresponding NOAA station at Sioux Falls. The two project sites at Brown and Beadle counties have moderate percentage of data match. However, the other six project sites show a low percentage of maximum temperature data match with the corresponding NOAA stations. The

percentage of data match increases with the increase in tolerance limit (±1°F, ±2°F, ±3°F, ±4°F, ±5°F).

- It is apparent from the analysis that that there is no direct relationship between the data match percentage, and the distance of project site and NOAA station.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

The thesis has analyzed the effect of temperature on asphalt paving works in South Dakota. The process involved the analysis of maximum temperature at different locations of South Dakota both annually and monthly. One of the objectives of the thesis is to determine if the number of adverse weather days increased in the last 30 years (1991-2020) compared to the value reported in the 1998 SD DOT study. The results show that the NOAA stations generally have more 7-year moving average annual threshold (45°F) violation days than the State average (101.3) for South Dakota, except the Belle Fourche station. However, the NOAA stations have less 7-year moving average annual threshold (40°F) violation days than the State average (101.3), except the Aberdeen station. The analysis of average threshold violation days is also conducted for the months of January, April, and October. For all these months, the average threshold violation days are generally greater than the State average adverse weather days (South Dakota DOT, 2015) of that corresponding month at 45°F threshold. However, the average threshold violation days are generally less than the State average when the threshold is 40°F. It implies that by lowering threshold of maximum temperature, the expected adverse weather days can be reduced.

In general, the average threshold violation days are less than the State average adverse weather days (South Dakota DOT, 2015) when the threshold is 40°F, which leads to more working days. Also, the asphalt paving works might be extended beyond seasonal limits (May 1 to October 15 (inclusive)) set by SD DOT (South Dakota DOT, 2015). However, for a compacted thickness of more than 1 inch of surface course, the

minimum temperature is set at 40°F (South Dakota DOT, 2015). So, the lift thickness of surface course must be greater than 1 inch, when the temperature during asphalt paving is between 40°F and 45°F.

Another objective of the thesis is to determine if the maximum temperature data of the closest weather stations matches the weekly progress report (WPR) data for a subset of project sites. Most of the project sites (6 out of 9) show a low percentage of maximum temperature data match with the corresponding NOAA stations. Only the project site at Minnehaha County has a very high (98.3%) percentage data match. The project sites at Brown and Beadle counties show moderate percentage of data match. It is apparent from the analysis that that there is no direct relationship between the data match percentage, and the distance of project site and NOAA station.

5.2. Recommendations

Based on the conclusions of the thesis, future works can be conducted considering several other factors. The thesis dealt with 10 weather stations found from the National Oceanic and Atmospheric Administration (NOAA) website and 10 project sites found from Weekly Progress Report at different locations of South Dakota. Although the weather stations and project sites have spatially covered most directions of South Dakota, more weather stations and project sites can increase the accuracy of the analysis. At least, one weather station from each county can be included in the analysis to represent the geological and weather characteristics of the whole state.

Some road construction works like asphalt paving depend on the amount of daylight time. Since the amount of daylight varies at different seasons all over the year, the ‘total daylight’ parameter can be included in the analysis. The National Oceanic and

Atmospheric Administration (NOAA) website has the data for sunrise, sunset, solar noon, and solar position. The 'total daylight' can be found by subtracting sunset time from sunrise time. It can help to set contract time.

Soil properties can be incorporated in the analysis since asphalt paving cannot be done on wet or frozen soil (South Dakota DOT, 2015). For example, after rainfall overnight, the drainage property of soil may provide information about the site condition on the next working day. Soil data are available for public access from the USDA Natural Resources Conservation Service at the Web Soil Survey (Natural Resources Conservation Service, 2023). The soil data can be used to create thematic maps for South Dakota as shown in Figure 37. It shows that most of the soil of South Dakota represents either Group B or Group D. Group B soils have a moderate infiltration rate when thoroughly wet. On the other hand, Group D soils have a very slow infiltration rate (high runoff potential) when thoroughly wet. This information along with other soil properties can be included in the analysis.

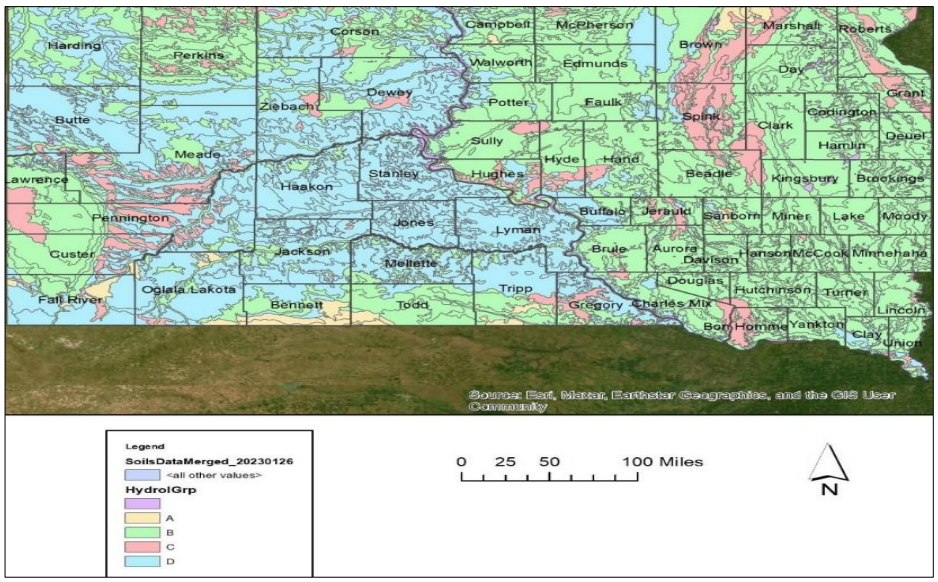


Figure 37. Thematic map based on hydrologic soil group

Figure 37 shows that most of the soil of South Dakota represents either Group B or Group D. Group B soils have a moderate infiltration rate when thoroughly wet. On the other hand, Group D soils have a very slow infiltration rate (high runoff potential) when thoroughly wet. This information along with other soil properties can be included in the analysis.

The comparison of the WPR vs. NOAA data shows that most of the project sites have a low percentage of maximum temperature data match with the corresponding NOAA stations. If the elevation of the project sites and NOAA stations can be incorporated in the analysis, it may provide more insights into the data match comparison.

REFERENCES

AIA (American Institute of Architects). (2007). General conditions of the contract for construction. *A201-2007*.

Anastasopoulos, P. C., Labi, S., Bhargava, A., & Mannering, F. L. (2012). Empirical assessment of the likelihood and duration of highway project time delays. *Journal of Construction Engineering and Management*, *138*(3), 390-398.

Apipattanavis, S., Sabol, K., Molenaar, K. R., Rajagopalan, B., Xi, Y., Blackard, B., & Patil, S. (2010). Integrated framework for quantifying and predicting weather-related highway construction delays. *Journal of construction engineering and management*, *136*(11), 1160-1168.

Ballesteros-Perez, P., Kabiri, S., Smith, S. T., & Hughes, W. (2016). Dealing with weather-related claims in construction contracts: A new approach.

Chan, E. H., & Au, M. C. (2008). Relationship between organizational sizes and contractors' risk pricing behaviors for weather risk under different project values and durations. *Journal of Construction Engineering and Management*, *134*(9), 673-680.

Connors, R. B. (2003). Weather derivatives allow construction to hedge weather risk. *Cost Engineering*, *45*(3), 21.

FHWA (Federal Highway Administration). (2002). FHWA guide for construction contract time determination procedures.

Gondy, C., & Hildreth, J. (2007). Contract Time Determination Guidelines.

Herbsman, Z. J., & Ellis, R. (1995). *Determination of contract time for highway construction projects* (No. Project 20-5 FY 1992).

Ibbs, W., & Kang, J. M. (2018). Weather-related delay provisions in public transportation construction contracts. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, *10*(3), 04518009.

Ibbs, W., & Sun, X. (2017). Weather's effect on construction labor productivity. *Journal of legal affairs and dispute resolution in engineering and construction*, *9*(2), 04517002.

Iowa, D. O. T. (2012). Standard specifications for highway and bridge construction. *Iowa Department of Transportation, Ames, IA*.

Jeong, H. D., Gransberg, D. D., Touran, A., Choi, K., & Rahgozar, M. (2022). *Systematic Approach for Determining Construction Contract Time: A Guidebook*. Transportation Research Board.

Kartam, S. (1999). Generic methodology for analyzing delay claims. *Journal of construction engineering and management*, *125*(6), 409-419.

Karthick, S., Kermanshachi, S., & Pamidimukkala, A. (2023). Analysis of the Health and Safety Challenges Faced by Construction Workers in Extreme Hot Weather Conditions. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, *15*(1), 04522048.

Kenner, S., Johnson, R. L., Matt, S. A., Miller, J. R., & Salmen, J. A. (1998). Development of working day weather charts for transportation construction in south Dakota.

Koehn, E., & Brown, G. (1985). Climatic effects on construction. *Journal of Construction Engineering and Management*, *111*(2), 129-137.

Levin, P. (1998, May). Construction contract claims, changes & dispute resolution. American Society of Civil Engineers.

Michigan DOT. (2002, October). Guide for Contract Time Determination (CTD) Procedures.

MNDOT (Minnesota DOT). (2020). Standard specifications for construction.

Moselhi, O., & El-Rayes, K. (2002). Analyzing weather-related construction claims. *Cost engineering*, *44*(8), 12.

Moselhi, O., Gong, D., & El-Rayes, K. (1997). Estimating weather impact on the duration of construction activities. *Canadian Journal of Civil Engineering*, *24*(3), 359-366.

MTDOT (Montana DOT). (2020). Standard and supplemental specifications for road and bridge construction.

National Cooperative Highway Research Program (NCHRP). (1978). Effect of weather on highway construction. *NCHRP Synthesis 47*.

National Cooperative Highway Research Program (NCHRP). (1981). Contract Time Determination. *NCHRP Synthesis 79*.

National Oceanic and Atmospheric Administration. (2022, August 25). *Climate Data Online Search*. https://www.ncdc.noaa.gov/cdo-web/search

Natural Resources Conservation Service. (2023, December 10). *Web Soil Survey - Home*. https://websoilsurvey.sc.egov.usda.gov/app/

NDDOT (North Dakota DOT). (2022). Standard specifications for road and bridge construction.

Nebraska, D. O. T. (2017). Standard specifications for highway construction. *Lincoln, NE: Nebraska Department of Transportation. Retrieved November*, *1*, 2017.

Nguyen, L. D., Kneppers, J., García de Soto, B., & Ibbs, W. (2010). Analysis of adverse weather for excusable delays. *Journal of construction engineering and management*, *136*(12), 1258-1267.

Okere, G. (2019). An evaluation of a predictive conceptual method for contract time determination on highway projects based on project types. *International Journal of Civil Engineering*, *17*(7), 1057-1073.

Puetz, J. A. (2013). Analysis of Historical Cooperative Observation Program (COOP) Climate Data Through Trend and Correlation Determination for Selected South Dakota Sites and Comparisons of COOP Sensors with the Automated Weather Data Network (AWDN) Remote Sensors.

Russo Jr, J. A. (1966). The economic impact of weather on the construction industry of the United States. *Bulletin of the American Meteorological Society*, *47*(12), 967-972.

Schuldt, S. J., Nicholson, M. R., Adams, Y. A., & Delorit, J. D. (2021). Weather-related construction delays in a changing climate: a systematic state-of-the-art review. *Sustainability*, *13*(5), 2861.

SDDOT (South Dakota DOT). (2015). Standard specifications for roads and bridges.

Semple, C., Hartman, F. T., & Jergeas, G. (1994). Construction claims and disputes: Causes and cost/time overruns. *Journal of construction engineering and management*, *120*(4), 785-795.

Senouci, A. B., & Mubarak, S. A. (2016). Multiobjective optimization model for scheduling of construction projects under extreme weather. *Journal of Civil Engineering and Management*, *22*(3), 373-381.

Shahin, A., AbouRizk, S. M., & Mohamed, Y. (2011). Modeling weather-sensitive construction activity using simulation. *Journal of construction engineering and management*, *137*(3), 238-246.

Thomas, H. R., & Ellis Jr, R. D. (2009). Fundamental principles of weather mitigation. *Practice Periodical on Structural Design and Construction*, *14*(1), 29-35.

Thorpe, D., & Karan, E. P. (2008). Method for calculating schedule delay considering weather conditions. In *Proceedings of the 24th annual conference of the Association of Researchers in Construction Management (ARCOM 2008)* (Vol. 2, pp. 809-818). Association of Researchers in Construction Management (ARCOM).

WYDOT (Wyoming DOT). (2021). Standard specifications for road and bridge construction.