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Changes of Winter Severity in Arkansas during 1901-2100

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Abstract

The objective of this study was to quantify the winter severity in a way that was reproduceable and easy to understand. The Accumulated Winter Severity Seasonal Index (AWSSI) was chosen for this reason and was used to quantify winter severity by season across the state of Arkansas. The variables that go into the AWSSI calculation are maximum daily temperature, minimum daily temperature, daily snowfall, and daily snow depth. When the snowfall and snow depth were missing, they can be estimated using daily temperature and precipitation. Then the estimated snowfall and snow depth can be subsequently used to quantify the winter severity. The AWSSI calculated this way is named as (Precipitation Accumulated Winter Severity Seasonal Index) pAWSSI. Our evaluations suggested that pAWSSI can reasonably reproduce the temporal variation of AWSSI. Due to scarce snowfall and snow depth data in Arkansas, this study used the pAWSSI to examine the spatial and temporal variations of winter severity in Arkansas from 1901-2012 based on observations and from 2012-2100 based on multiple climate model simulations.

The long-term averaged pAWSSI suggested more harsher winter in the north and northwest Arkansas. The state averaged AWSSI suggest notable interannual variability. The most severe winters occurred in late 1970s and earlier 1980s, likely due to several severe snow storms in these years. There is an overall weak downward trend before middle 1970s, followed by notable decreasing AWSSI scores, suggesting less harsher winters in recent decades. However, the start, end, and length of winter season in AR show weak spatial and temporal variations.

The temporal variations in pAWSSI are largely controlled by winter temperature. There was less snowfall in warm winters and hence smaller pAWSSI. The decreasing pAWSSI (less cold winter) is associated with warming temperature, especially in the recent several decades. The temporal variations of pAWSSI are also influenced by large-scale atmospheric and oceanic indices. On interannual time scale, the winters with higher pAWSSI scores are usually associated with negative North Atlantic Oscillation (NAO) phases. The milder winters during 1990s and 2000s are associated with positive NAO phases. The pAWSSI is also significantly correlated with Pacific Decadal Oscillation (PDO) during 1948-2012. However, the link between PDO and pAWSSI weakened during recent two decades, suggested that the impacts of PDO on winter severity in Arkansas may change on decadal time scales.

The daily temperature and precipitation from 20 CMIP5 models under the RCP8.5 scenario were also used to evaluate the winter severity in AR in the future. The pAWSSI for individual models was calculated. The ensemble mean pAWSSI of the 20 CMIP5 models show similar long-term averaged and trend as that based on observations during 1950-2012, suggesting that the models did a reasonable job in simulating the temporal variations of pAWSSI. The models projected accelerating decreasing trend in pAWSSI from 2006-2100, suggesting that the projected climate changes can cause pronounced decrease in winter severity. Compared to the present-day condition, the pAWSSI in Arkansas may decrease 65-75% by the end of this century.

Acknowledgments

The author of this thesis would like to thank Dr. Song Feng for taking him in and giving him the opportunity to attend graduate school and for his overall guidance and mentorship along the way. Also, would like to extend my gratitude to Dr. Mohamed Aly, Dr. Linyin Cheng, and Dr. Ted Holland for all your help and support. I would like to also thank Dr. Fred Limp and everyone at CAST for your support and giving me the opportunity and experience of being a teaching assistant. I want to extend a special thank you to Dr. Chang Liu for all your help with the charts and data calculation. Most importantly, I want to thank my wife Maria, son Mateo for enduring the long hours of work I had to put in during my time in graduate school and writing this thesis. I would also like to acknowledge my parents Gloria and Juan Garcia for the scarifies you had to make coming to the United States to give me and my siblings Ebony and Alexander Garcia a better life and supporting me along the way.

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Chapter 1: Introduction

It is a general consensus that recent global warming is caused by human activities, predominantly the burning of fossil fuels and deforestation (IPCC, 2021, NCA, 2014). The warming is most evident in the middle and high latitude Northern Hemisphere in recent decades. The warming rate in the cool season is also faster than the warming season. The temperature in the United States has also increased by 1.3F to 1.9F since 1895, with most of the warming occurring since the 1970s (NCA, 2014). The warming is more pronounced in the northern and western United States, especially in winter and spring. Changes in precipitation are less homogeneous. The wet regions became wetter while the dry regions became even drier (NCA, 2014). For example, the annual precipitation has decreased in much of the west and Southwest United States.

The warming temperatures have caused higher frequency of extreme weather events, such as more extreme floods and droughts (NCA, 2014). Prolonged periods of extreme hot temperatures have been observed in much of the United States in recent 50 years. Many parts of the Northern Hemisphere are experiencing a decrease in frequency of arctic and polar air intrusions (Salinger, 2005), which led to less frequent and less intense cold waves. On the other hand, the spring started earlier while the fall arrived later in recent 100 years, which jointly led to longer growing season in the United States (Marinaro, 2015, McCabe et al., 2015)

1.2 Climate Change Impacts

Changes in climate and extremes can have a drastic effect on crop yield and global food supply. For example, the drought and associated water shortage in the Central United States in 2012 has caused the corn and soybean yield to decline by 30%. The estimated economic loss for this drought is over $30 billion. Mirek et al (2019) found that increased drought has led to increased food prices and could become exponentially higher when factoring in the effects of climate change in the near future. They further argued that up to 60 percent of the wheat-growing areas could see simultaneous, severe, and prolonged droughts by the end of the century, which could further disrupt global food production and price. Besides droughts and water shortage, rising temperature and more frequent heatwaves can also adversely influence food production. Lobell (2011) found that the maize and wheat production has declined by 3.8 and 5.5%, respectively from 1980 to 2008. Therefore, the joint impacts of warming and increasing extremes will exacerbate food insecurity in areas currently vulnerable to hunger and undernutrition (Wheeler and Braun, 2013). Access to food could be indirectly affected by collateral effects on household and individual incomes, as well as a decrease in access to clean drinking water and damage to health.

Due to large land mass in the United States, the agriculture in some regions appear to be more susceptible to climate change (National Climate Assessment, 2014). Regions in the mid-south such as Arkansas rely heavily on agriculture could be greatly affected by a higher frequency of weather extremes and climate variability (EPA, 2016). According to the EPA, Arkansas will become warmer, and the state will probably experience more severe floods and drought. Arkansas has not warmed at the same rate as most of the United States in the last 50 to 100 years, but the annual rainfall has increased for much of the state. With the increased rainfall the state will become increasingly prone to flash flooding with heavy amounts of rainfall occurring in a short period of time. These changes in climate are likely to cause an increase in storm damage, harm livestock, and reduce crop yields.

1.3 Winter Severity Impacts

Besides the impact of climate changes on agriculture and many other sectors (NCA, 2014), the winter weather extremes have also been notably influenced by the warming temperature. The extremes weather in winter can directly or indirectly affect many economic sectors, including public health related to air quality and thermal comfort levels, loss of crops, missed work and school days, roadway safety, as well as the behavior of wild animals and vegetation (Changnon, 1979). Being able to quantify and analyze the severity of winter is one way of looking at climate change and how winter seasons have varied during the past and the future. It is of interest to examine whether the winter is getting colder and more extreme or milder with less wintery weather.

The severity of winter can be quantified using a single climate variable. For example, Lyness and Badger (1969) used the total temperature accumulation based on daily maximum and minimum temperatures throughout a winter season to quantify winter severity. The snowfall, on the other hand, is another frequently used climate variable to examine the harshness of winter. Changnon et al (2006) used daily snowfall from 1222 weather stations across the United States to examine the spatial and temporal features of snowstorms. They found that the geographical patterns of average and peak storm areas are closely linked to seasonal upper-level circulation patterns and the synoptic conditions. Months of greatest storm activity exhibit great spatial variability across the United States. December is the peak month in the lee of the Great Lakes, and January is the peak of storm activity over large parts of the West, South, Midwest, and East. Storm frequencies maximize in February in an east–west area across the south-central United States, including Arkansas. March and April are the peak months for snowstorms in the high plains and the northern Rockies, respectively. Areas with months of peaks of storm activity are also areas in which the highest average total snowfall occurs in that same month (Changnon et al., 2006). A more detailed study by NOAA (2010) found that the years with heavy seasonal snow and extreme snowstorms in the United States continue to occur with great frequency as the climate has changed. In the eastern two-thirds of the contiguous United States, the prevalence of extreme winter storms has increased during the last century. Approximately twice as many extreme U.S. snowstorms occurred in the latter half of the 20th century than the first (NOAA, 2010).

Multiple climate variables were also combined to quantify their joint impacts on winter severity. The variables considered in individual winter indexes vary and depending on the specific purposes or specific regions. Verme (1968) developed a winter severity index called the “Chill-o-Meter” for Northern Michigan peninsula. This index uses temperature and precipitation, in addition to components of temperate and precipitation like windchill and snow depth to calculate the winter severity and its impact on whitetail deer (Verme, 1968). Specifically, Verme (1968) assigned a point score for temperate, wind chill, and snow depth and added them together to get a total severity index number on a weekly basis. It was found that this index is an important factor that caused the loss of whitetail deer, especially when the index reaches a critical point. For example, the index rating of over 100 for a period of 16 to 20 weeks can be life threatening for deer in the upper Michigan peninsula.

Fisk (2008) investigated the statistical nature between same-day surface temperature and precipitation with daily snowfall using a multivariate regression analysis in Minneapolis–St. Paul, Minnesota. Then they developed a winter severity index and assigned a winter season into groups labeled as “cold’’ or ‘‘mild’’ for temperatures and ‘‘light,’’ ‘‘moderate,’’ or ‘‘heavy’’ for precipitation (Fisk, 2008). McCullouch et al (2004) used seven parameters (frost day, freezing rain, drifting snow, snow depth, storm intensity, and average temperate) to developed a winter severity index for the state of Indiana. The index was developed with inspiration from past winter severity indices developed by the Washington (Mahoney, 1985) and Wisconsin Highway Departments (Adams, 2001). It was found that the index can be used to estimate snow and ice removal expenditures and the amount of manpower needed.

The work completed by McCullouch et al. (2004) and much of the other work done in the subject of winter severity and variability can be improved and constantly changing as new data is collected and new discoveries are made. Boustead et al (2015) developed the Accumulated Winter Season Severity Index (AWSSI), which combines some widely used climate variables to quantify the severity, start, end and duration of winter. Some evaluations suggested that this index can be used at any given year and location (Boustead et al., 2015). Marinaro et al. (2015) used the AWSSI to evaluate the winter of 2013-2014 in the Midwestern United States and compared to other winters since 1950. They found that 2013-2014 was a very harsh winter for the Great Lakes area and the entire Midwest, with record ice cover in the Great Lakes not seen since the 1970s and record amounts of flight cancellations. This work laid the groundwork for creating a modern rating system for winter severity, the accumulated winter severity seasonal index (AWSSI).

1.4 Physical processes that influence the winter climate

The physical mechanisms that influence winter climate were also examined in many previous studies. The conditions that influencing the severity of eastern U.S. snowstorms include warmer-than-average ocean surface temperatures in the Atlantic, which can lead to high amounts of moisture flowing into a storm and contribute to greater intensification of the storm (NOAA, 2010). Recent research has also shown that the increasing surface temperatures and reduction in Arctic Sea ice may produce atmospheric circulation patterns that are favorable for winter storm development in the eastern United States (Francis & Vavrus, 2012). Specifically, high-pressure blocking patterns over the North Atlantic are becoming more common. This blocking patterns lead to cold outbreaks in the eastern United States along with slower moving mid-latitude cyclones. This combined with the warmer sea surface temperatures and available moisture can result in very intense winter storms.

Because the large-scale climate indices (i.e., El Nino Southern Oscillation (ENSO), North Atlantic Oscillation (NAO)) can significantly impact the winter climate, it is expected that they can individually or jointly influence the severity of winter. In fact, Marinaro et al., 2015 found that the AWSSI in various Midwestern cities are influenced by the NAO. Liu et al (2021) found that the variations of AWSSI in North America are dominated by temperature, but the ENSO, Pacific Decadal Oscillation (PDO), and NAO can also significantly impact the winter severity.

However, few of previous studies focused on the winter climate and winter severity in the Southern United States, albeit the cold surges and ice storms can greatly affect the economic and public health in these regions. For example, a severe ice storm hit Northwest Arkansas in January 2009. It produced 1-3 inches of ice and collapsed the power support for about 350,000 people in this region. A recent example is the cold surge that influenced Texas in the middle of February 2021. This cold event claimed the lives of dozens of people and caused billions of dollars of personal property and infrastructure were damaged or destroyed.

Additionally, millions of people lost power, water and basic services. Therefore, it is also important to examine the severity of winter in in the southern United States (i.e., Arkansas) during the past and the future.

1.5 Goals and Objectives

The goal of this study is to examine the winter severity in Arkansas during the past based on observations and the future based on modeled daily climate data from the models participated in the Coupled Model Intercomparison Project Phase 5 (CMIP5). To address this goal, this study has the following two specific objectives:

1) Examine the changes of winter severity in Arkansas during 1901-2012.

   The AWSSI combined the temperature, snowfall and snow depth to quantify the severity of winter. However, there are only a few weather stations in Arkansas that have long and high-quality snow depth and snowfall observations, possibly because there are few snowfalls in this state. When snow depth and snowfall data are missing, they can be estimated using daily precipitation and temperature, which in turn can be used to calculate the AWSSI (termed as pAWSSI, Boustead et al., 2015). The AWSSI and pAWSSI in limited weather stations were firstly calculated and compared. Then the temporal variations of pAWSSI across Arkansas during 1901-2012 and their links to large-scale forcing's were analyzed. Details of these analysis can be found in Chapter 2.

2) Evaluate the future changes of AWSSI in Arkansas under different emission scenarios.

   The modeled daily temperature and precipitation during 2006-2100 in more than 20 CMIP5 models were used to estimate the pAWSSI in Arkansas. The emission scenarios analyzed include the RCP4.5 and RCP8.5.

The spatial and temporal variations of AWSSI in Arkansas will be visualized using GIS. GIS has traditionally been used in climate studies (i.e., Liu 2009) to develop a GIS based risk assessment tool for visualizing climate change impacts in agricultural industries and evaluating eventual adaptation strategies.

Chapter 2: Observed Changes in Winter Severity in Arkansas during 1901-2012

Abstract

The accumulated winter severity index (AWSSI) provides a way to quantify the winter severity in a given region. Using this index, this study examined the spatial and temporal variations of winter severity in Arkansas during 1901-2012. The changes in the start, end, and length of the winter season in the state were also examined. The long-term mean AWSSI in Arkansas is linked to latitude and altitude. The temporal variations of the state averaged AWSSI suggest weak trend before middle 1970s followed by notable decreasing AWSSI scores, suggesting less harsher winters in recent decades. However, the start, end, and length of winter season in AR show weak spatial and temporal variations. The AWSSI and its variations are largely influenced by winter temperature. The decreasing AWSSI (less cold winter) is associated with warming winters, especially in recent several decades. The temporal variations of AWSSI are also influenced by large-scale atmospheric and oceanic indices, such as the NAO and PDO.

2.1 Introduction

The severity of winter in a given region can directly and/or indirectly impact many different sectors of the ecosystems, economics, and public health. Snowstorms, ice and freezing temperatures damage heat, power, and transportation services, sometimes for days or weeks. During 1980-2021, there were 19 snowstorms and 9 freezing events that caused billion-dollar damage in the United States (US). The total costs of these events increased notably in the recent 10-15 years, albeit the number of these events decreased (Figure 2.1).

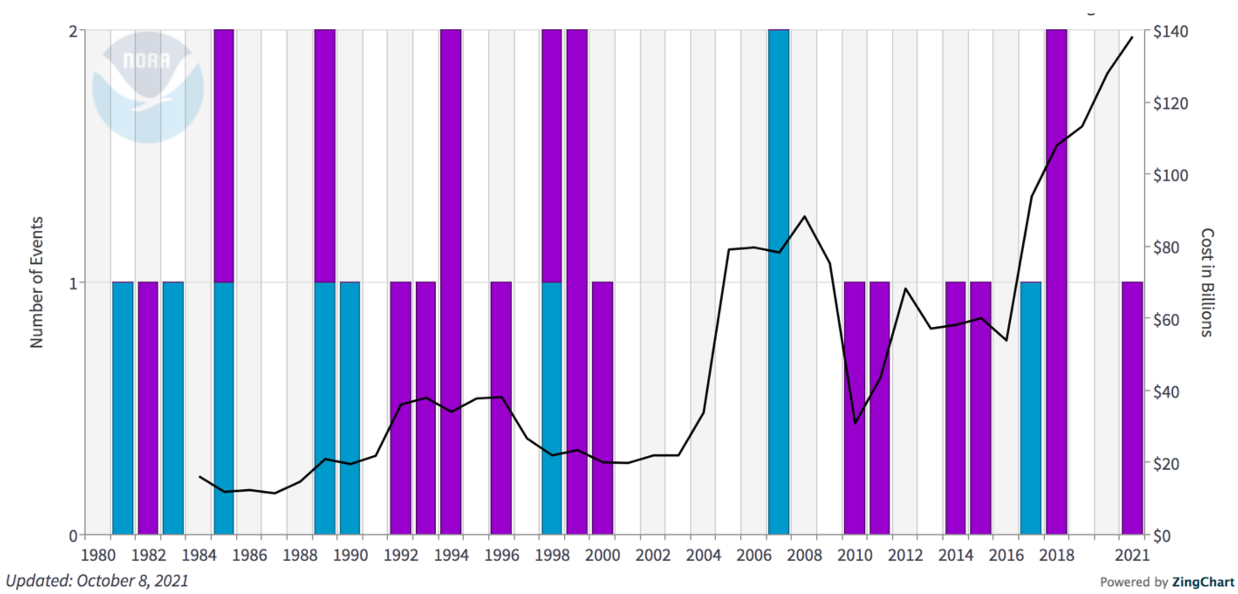


Figure 2.1. The temporal variations of number of winter storms (purple bars) and freeze events (blue bars) that costed more than $1.0 Billion in the United States during 1980-2021. The five-year average CPI-Adjusted costs are shown in black line.

The danger from winter weather varies across the US, with most of the snowstorms and freezing cold events occur in the northern and northeastern U.S. However, this does not mean that the warmer south and southeast US are immune to these winter disasters. For example, during December 15 to 25, 1983, a cold wave swiped across the east and southeast US. The severe freeze damages citrus crops across central/northern Florida. The total cost of this cold event is $5.6 (CPI-adjusted, https://www.ncdc.noaa.gov/billions/events). During February 10-19, 2021, a historic cold wave and winter storm impacted the central and eastern US. The temperature was more than 40^{o}F below normal from Nebraska to Texas. The frigid cold air caused widespread power outages and nearly 10 million people in the southern states without power. The cold air also frozen water pipes in Texas. The total cost of this cold wave is over $20.8 Billion (https://www.ncdc.noaa.gov/billions/events). Therefore, it is important to quantity the severity of winter weather and winter season.

Multiple indices were developed to quantify the winter season severity in the US (i.e., Carmichael et al., 2004; Schummer et al., 2010). Boustead et al. (2015) developed the accumulated winter season severity index (AWSSI), which combines temperature, snowfall and snow depth to quantity the severity of winter. This index gained widespread attention and has been used to evaluate the changes of winter severity in the Midwestern US (Marinaro et al., 2015) and North America (Liu et al., 2021). However, none of the previous studies focused on the winter severity in Arkansas. This chapter used AWSSI to examine the spatial and temporal variations of winter severity in Arkansas and their physical mechanisms during the instrumental period. The starting, end and length of the winter season in Arkansas were also analyzed.

2.2 Data and Methodology

2.2.1 The AWSSI and precipitation based AWSSI (pAWSSI)

The AWSSI was developed to be a site-specific threshold-based score of the severity of a winter season, in which points are assigned daily based on thresholds of maximum and minimum temperatures, snowfall, and snow depth (Boustead et al., 2015, Table 2.1). The daily scores were then summed up from the beginning to the end of a given winter season to quantify the overall severity of winter. The higher the score, the severer the winter. Based on Boustead et al. (2015), the beginning of winter is when the first of three conditions are met: 1) daily maximum temperature is less than or equal to 32 degrees F (0 degrees C), 2) daily snowfall is greater than or equal to 0.1in. (0.25cm), or 3) it is 1 December. Once one of these conditions is reached, AWSSI begins accumulating. The end of winter and cessation of AWSSI accumulation occurs when the last of the following four conditions is met: 1) daily maximum temperature is greater than or equal to 32 degrees F (0 degrees C) no longer occurs, 2) daily snowfall that is greater or equal to 0.1 in. (0.25 cm) no longer occurs, 3) daily snow depth that is greater than or equal to

1.0 in. (2.5 cm) no longer occurs, or 4) it is March 1st. The length of winter along with the maximum and minimum temperatures, snowfall, and snow depth all factor into the total accumulated daily AWSSI score.

	Temperature (°F)		Snow (in.)	
Points	Max	Min	Fall	Depth
1	25–32	25–32	0.1–0.9	1
2	20–24	20–24	1.0–1.9	2
3	15–19	15–19	2.0–2.9	3
4	10–14	10–14	3.0–3.9	4–5
5	5–9	5–9	—	6–8
6	0–4	0–4	4.0–4.9	9–11
7	From −1 to −5	From −1 to −5	5.0–5.9	12–14
8	From −6 to −10	From −6 to −10	—	15–17
9	From −11 to −15	From −11 to −15	6.0–6.9	18–23
10	From −16 to −20	From −16 to −20	7.0–7.0	24–35
11	—	From −20 to −25	—	—
12	—	—	8.0–8.9	—
13	—	—	9.0–9.9	—
14	—	—	10.0–11.9	—
15	<−20	From −26 to −35	—	≥36
18	—	—	12.0–14.9	—
20	—	<−35	—	—
22	—	—	15.0–17.9	—
26	—	—	18.0–23.9	—
36	—	—	24.0–29.9	—
45	—	—	≥30.0	—

Table 2.2.1 Point contributions to daily AWSSI scores as based on thresholds of daily maximum and minimum temperature, snowfall, and snow depth (Boustead et al., 2015).

There are only a few weather stations that have daily snowfall and snow depth observations in Arkansas, which makes it difficult to calculate AWSSI because it requires temperature, snowfall, and snow depth data. Fortunately, the snowfall and snow depth can be reasonably estimated using daily temperature and precipitation (Boustead et al., 2015). The estimated snowfall and snow depth can be subsequently used to determine the beginning and end of winter season as well as to calculate AWSSI (termed as precipitation based AWSSI, or pAWSSI). In this chapter, I used Steve Hilberg's Perl script to calculate estimated snowfall and snow depth totals, which were based on the method outlined by Boustead et al. (2015). The script that calculates pAWSSI takes an input file that includes dates, precipitation, snowfall (if available), snow depth (if available), maximum temperate, and minimum temperature. If the input data includes snowfall and snow depth data, the script will ignore it and move it over to the observed snowfall and observed snow depth fields in the results. Using both the maximum and minimum temperatures as well as precipitation data the script then calculates snowfall and snow depth. This new calculated snowfall and snow depth data can then be used to calculate the AWSSI for locations with missing snowfall and snow depth.

How confident can be with using pAWSSI for situations when snowfall and snow depth are unavailable? To address this question, I gathered weather data for Fayetteville, AR and Gravette, AR for the date ranges of 1986 to 2016. The two locations were chosen because continuous and non-missing observational temperature, precipitation, snowfall, and snow depth are available. I then calculated the AWSSI for both locations using temperature, snowfall, and snow depth, and pAWSSI using merely temperature and precipitation. The temporal variations in AWSSI and pAWSSI were then examined (see section 2.3.1).

To examine the spatial and temporal variations of winter severity in Arkansas, the daily maximum, minimum temperature and daily total precipitation on quarter degree resolution during 1901-2012 were retrieved from the Global Land Data Assimilation System (GLDAS, https://ldas.gsfc.nasa.gov/gldas/GLDASdownload.php). These data were used to calculate pAWSSI on individual grid points in Arkansas. The long-term mean and linear trend in pAWSSI, as well as the beginning, end, and length of winter season in Arkansas were calculated and examined.

2.2.2 Large scale oceanic and atmospheric indices

To understand the physical mechanisms that caused the changes in winter severity, the regional averaged pAWSSI, the starting, end and length of the winter season in Arkansas are correlated to several large-scale atmospheric and oceanic indices, including the North Atlantic Oscillation (NAO) and the Pacific Decadal Oscillation (PDO). Previous studies (i.e., Liu et al., 2021) suggested that these indices have strong impact on climate in the south and southeast U.S. The monthly NAO data from 1951 to 2012 was retrieved from https://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/nao.shtml. The monthly PDO index during 1901-2015 was obtained from the University of Washington (http://research.jisao.washington.edu/pdo/). The monthly NAO and PDO index were further used to calculate the winter (December, January, and February) values.

2.3 Results

2.3.1 Comparison of AWSSI and pAWSSI

Figures 2.2 and 2.3 show the temporal variations of AWSSI and pAWSSI in Fayetteville, AR and Gravette, AR, respectively. In general, the AWSSI and pAWSSI in the two locations show similar year to year variations, especially for Fayetteville, AR. The pAWSSI slightly underestimate the winter severity in winters with high AWSSI scores. Further investigation suggested that the snowfall and snow depth were underestimated using the methods outlined by Boustead et al (2015). For example, on February 9, 2011, Fayetteville received 14.6 inches of snowfall and the snow depth of 8 inches was recorded. This is one of the heaviest snowfalls to occur during 1986-2016. The estimated snowfall is only 6.2 inches, while the estimated snow depth is 6 inches, both smaller than the observations. The reason here could be that the liquid to snowfall ratio was greater than what the estimation calculated. Another reason is that the model cannot estimate ice accretion, which is quite common in the state of Arkansas in the winter months.

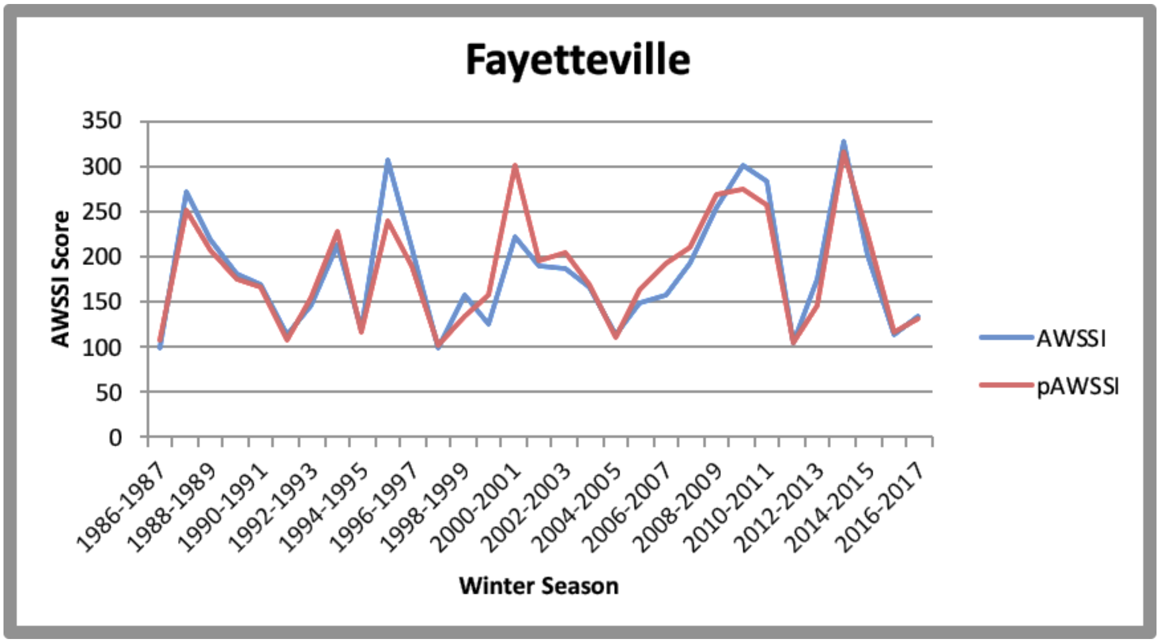


Figure 2.3.1 The temporal variations of AWSSI and pAWSSI scores for Fayetteville, AR from 1986 to 2017

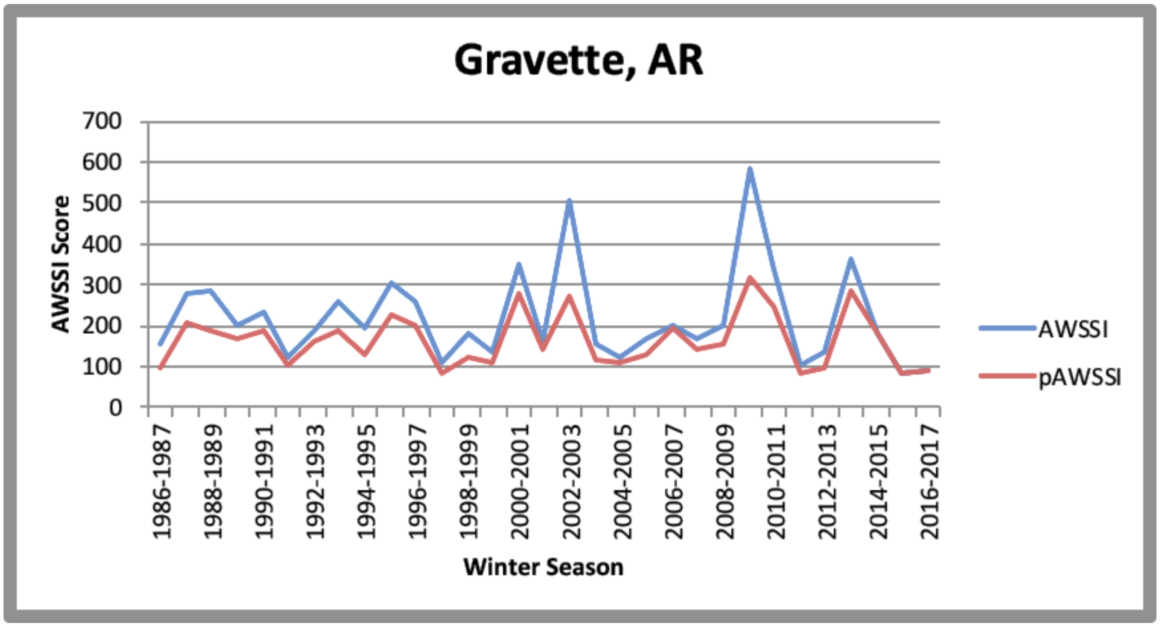


Figure 2.3.2 The temporal variations of AWSSI and pAWSSI scores for Gravette, AR from 1986 to 2017

The length of a winter season is very important when it comes to total AWSSI scores. Figures 2.4 and 2.5 illustrate the temporal variations of the winter season length in Fayetteville and Gravette, AR, respectively. There are several differences in the total length of winter seasons can be found when comparing the estimated length of days (pAWSSI) and observed length of days (AWSSI). The spike in the length of days for the winter of 2012-13 can be explained by a late season snowfall that occurred on May 5, 2013. The pAWSSI failed to estimate a meaning snowfall and snow depth for that day because the temperature is relatively milder. As a result, the length of winter season for the 2012-13 winter was significantly underestimated based on the estimated snowfall and snow depth.

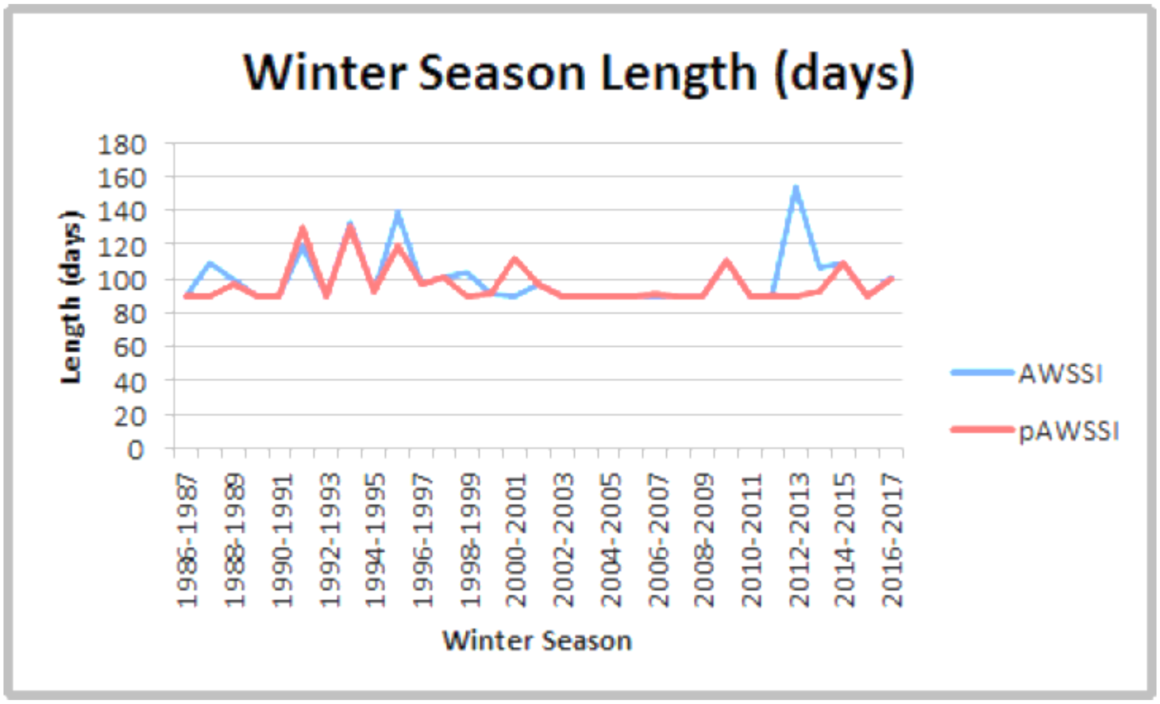


Figure 2.3.3 The temporal variations of the length of winter season for Fayetteville, AR from 1986 to 2017

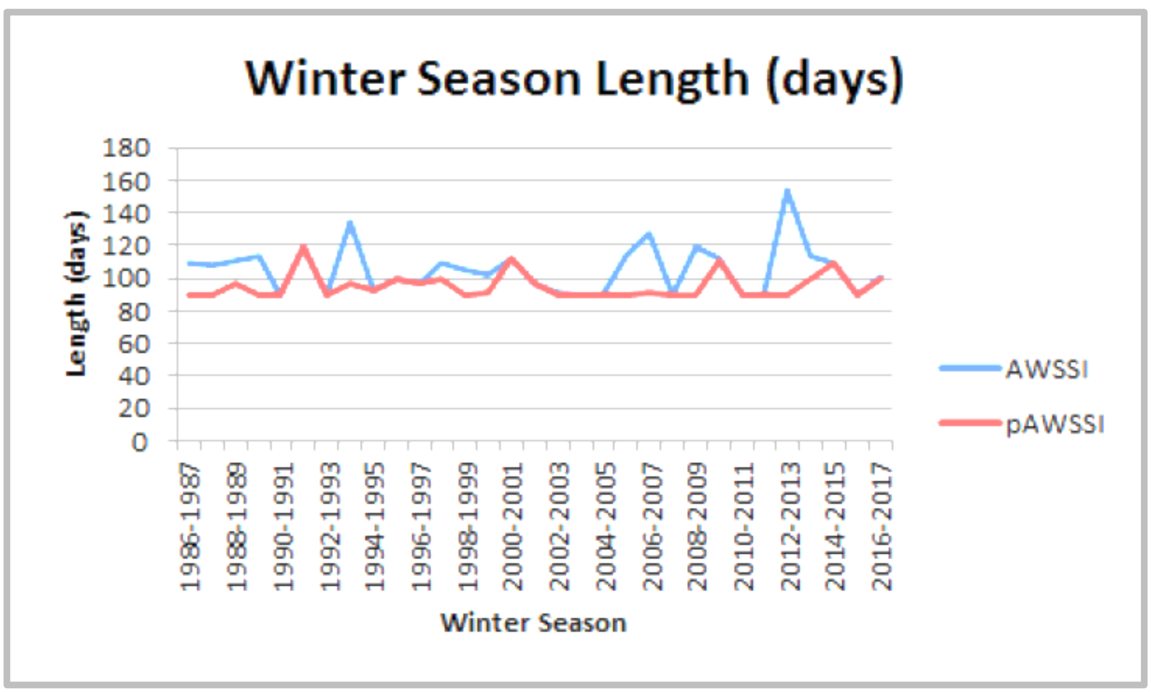


Figure 2.3.4 The temporal variations of the length of winter season for Gravette, AR from 1986 to 2017

In general, Figures 2.3.1-2.3.4 suggested that the method outlined by Boustead et al (2015) underestimated the snowfall and snow depth, which in turn underestimated the length of winter season and winter severity. Despite this discrepancy, the temporal variations of winter severity and the length of winter season can be reasonably estimated. In the following, I will focus merely on pAWSSI to understand the spatial and temporal variations of winter severity in AR because the snowfall and snow depth data in AR are scarce.

2.3.2 Changes in pAWSSI, starting and end of the winter season in Arkansas

To better visualize and interpret the changes in winter severity in the state of Arkansas, the long-term mean, and trends for pAWSSI, as well as the beginning, end and length of winter season were analyzed.

Figure 2.3.5 shows the spatial distribution of the average AWSSI in Arkansas from 1971 to 2000. The long-term averaged AWSSI is dependent on the latitude and altitude. Higher AWSSI scores appear in the northern and northwestern AR, while low AWSSI can be found in the southern AR. For the northwestern parts of Arkansas, the long-term mean AWSSI score is about 140. This number is notably smaller than many cities in the north and northeastern US. For example, the long-term average AWSSI score in Chicago is about 550 (Midwestern Regional Climate Center). Therefore, even the northernmost section of Arkansas still sees a light winter compared to cities further north of the continental United States.

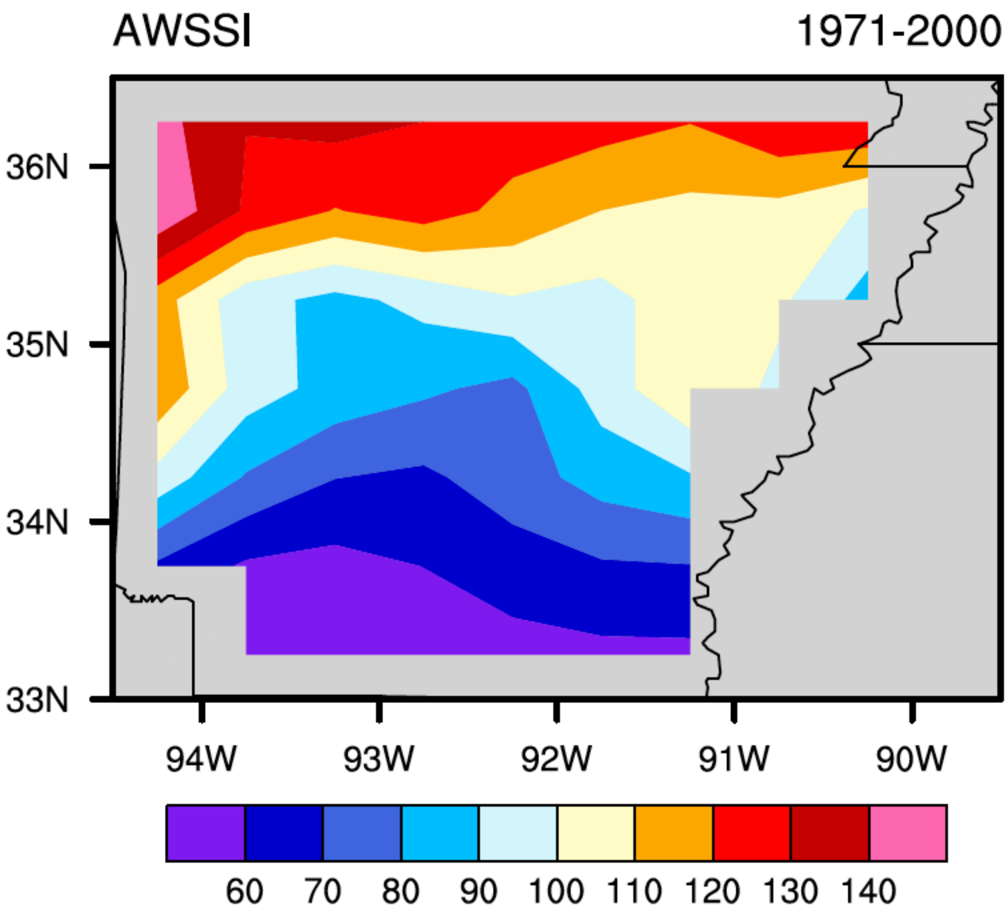


Figure 2.3.5 The long-term mean AWSSI scores for the state of Arkansas during 1971-2000.

Figure 2.3.6 shows the temporal variations of the Arkansas averaged pAWSSI from 1901 to 2012. Considerable year to year variations can be found during the past 100 years. The warmest winter appeared in 1936, with a pAWSSI score of 30. The coldest winter occurred in 1980. The pAWSSI score in this year is over 230, which is more than 7 times higher than that of 1936. Additionally, there is no notable long-term trend during the past 100 years, especially during 1901 to early 1970s. The winter seasons of the late 1970s are notoriously known to have been harsh winters for the state of Arkansas along with the rest of the region. Table 2.2 shows the snow fall totals for the 1970s for Fort Smith which verifies the harsh winters of the late 1970s seen in the AWSSI trends. The winter of 1978 is the second snowiest on record for Fort Smith.

The harsh late winters of the 1970s in Arkansas can also be seen in table 2.3 below as the winters of 1977-1978 and 1976-1977 are ranked second and third in all time most snowfall for Fayetteville. The AWSSI spatial averages align well with the coldest and snowiest parts of the state being the Northwestern and Northeastern areas in the late 1970s to early 1980s. However, it is easy to see that the average AWSSI scores are decreasing since late 1970s, suggesting less harsh winters in recent several decades.

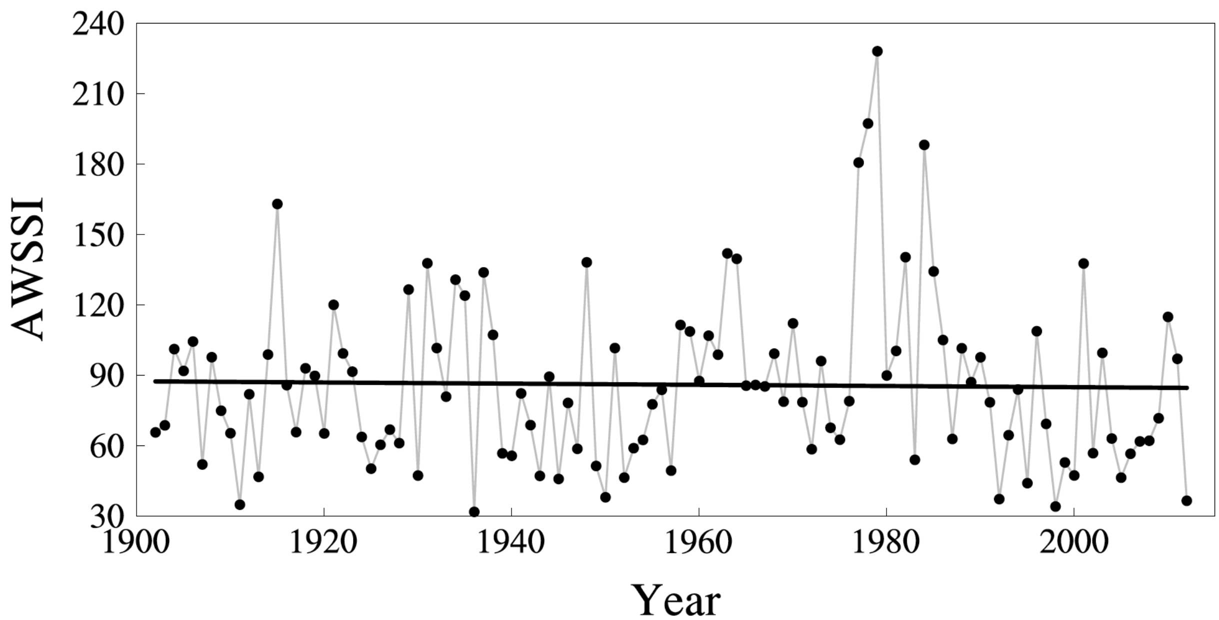


Figure 2.3.6 Time series plot of average yearly AWSSI for Arkansas. The black line represents the trend from 1901 to 2012

Fort Smith, AR - Snowfall Totals by Month and Year - The 1970s													
YEAR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1979	11.8	4.4	0	0	0	0	0	0	0	0	T	0	16.2
1978	11.7	10.0	0.2	0	0	0	0	0	0	0	0	T	21.9
1977	13.0	T	0	0	0	0	0	0	0	0	T	T	13.0
1976	T	0	0	0	0	0	0	0	0	0	4.7	0	4.7
1975	0	5.8	1.8	0	0	0	0	0	0	0	2.7	7.2	17.5
1974	T	0.3	0	0	0	0	0	0	0	0	2.0	T	2.3
1973	4.4	T	0	T	0	0	0	0	0	0	0	1.8	6.2
1972	0.3	0.5	0	0	0	0	0	0	0	0	1.7	0.7	3.2
1971	T	0.3	1.6	T	0	0	0	0	0	0	2.8	2.0	6.7
1970	5.2	T	0.2	0	0	0	0	0	0	0	0	0	5.4

Table 2.2 Snowfall totals by Month and Year for Fort Smith, AR in the 1970s

Fayetteville, AR - Maximum and Minimum Snowfall by Season				
Rank	Maximum	Season	Minimum	Season
1	33.0	2009-10	0.0	2006-07
2	23.5	1977-78	0.0	1999-00
3	22.0	1976-77	T	2015-16
4	21.7	1969-70	0.3	1962-63
5	20.5	1959-60	0.4	2017-18
6	20.3	2010-11	0.5	2007-08
7	18.1	1995-96	0.6	1949-50
8	17.3	1978-79	0.8	2011-12
9	16.3	1967-68	1.0	2008-09
10	15.9	2002-03	1.0	1956-57

Records began August 1949.

Table 2.3 Ranked maximum and minimum snowfall by season for Fayetteville, AR

Along with looking at AWSSI we can also look at some other variables such as the start, end and length of the winter season. The spatial distribution of the average start date of the winter season is shown in Figure 2.3.7. On average the winter season begins in late November for most of northern Arkansas and early December for the southern half of the state.

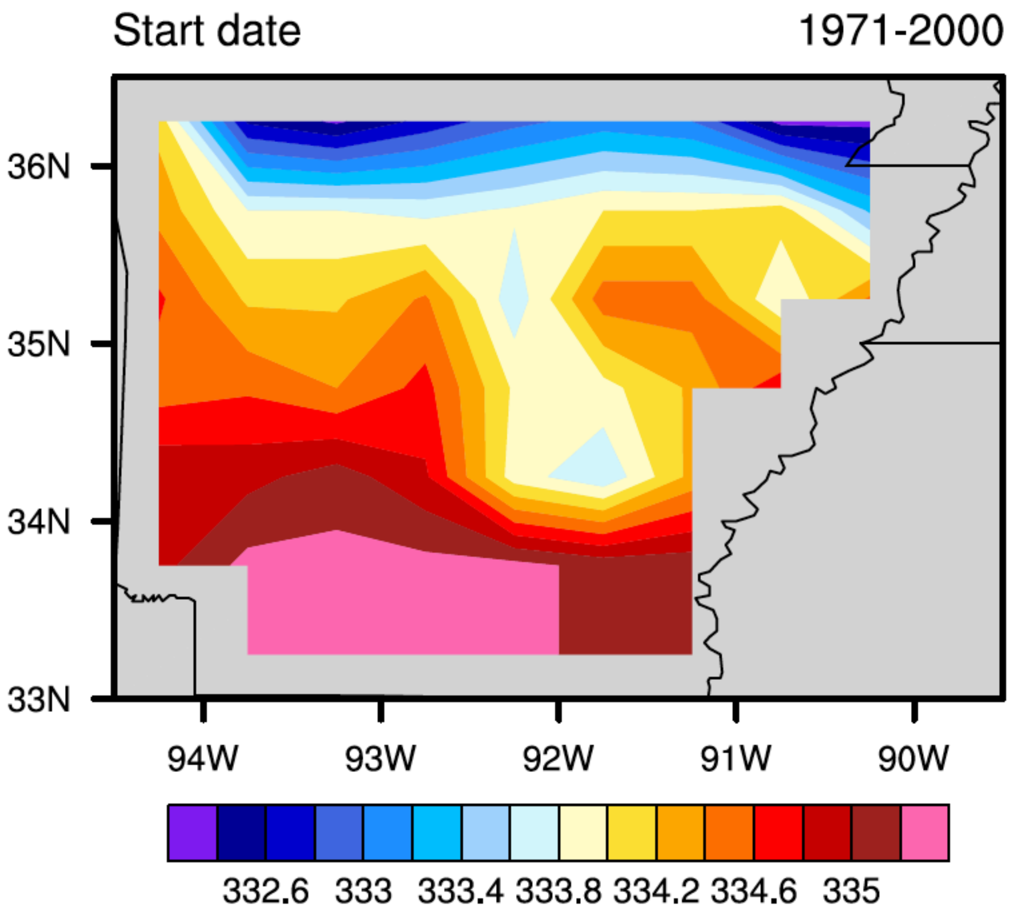


Figure 2.3.7 Average start of winter season by day of the year (1 would be equal to Jan.1 and 365 would be equal to Dec. 31) for the state of Arkansas from 1971-2000

The state averaged start data of the winter season in Arkansas is shown in Figure 2.3.8. The beginning of the winter season in Arkansas is stable generally beginning between the 334th (November 29th) and 336th (December 1st) day of the year. This means the daily maximum temperatures are not less than or equal to 32 degrees F or have any daily snow greater than or equal to 0.1in. until after December 1st for much of the state (see section 2.2.1 for the definition of winter season onset). There is a noticeable increase in the last couple of years that would be worth watching. The start of the winter season stays about average for the time frame of 1901-2012, but there are some outliers for example in the mid 1970s and into the early 1980s. This is consistent with what can be seen in tables 2.2 and 2.3 where the winters of the mid of late 1970's where colder and had more snow then average.

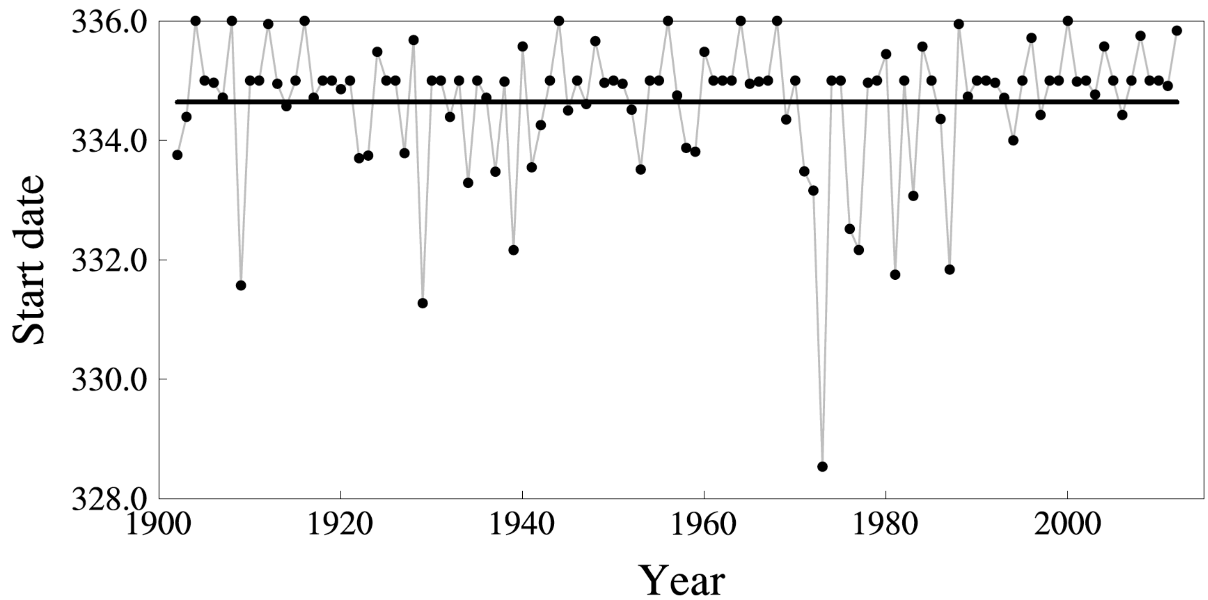


Figure 2.3.8 Time series plot of average starting date of winter season for Arkansas. The black line represents the trend from 1901 to 2012. The unit is day of year.

The end of the winter season is another variable considered by AWSSI. The length of the winter season as defined by AWSSI is an important variable to study. This can tell us if there are any changes in the length of the winter season which can be a major factor is the severity of the winter season. On average for the state of Arkansas the length of the winter season is about 92 days. As seen in Figure 2.3.9 below, the spatial distribution of the end of the winter season varies on the latitude of the state. Areas further north have a slightly later end of the winter season.

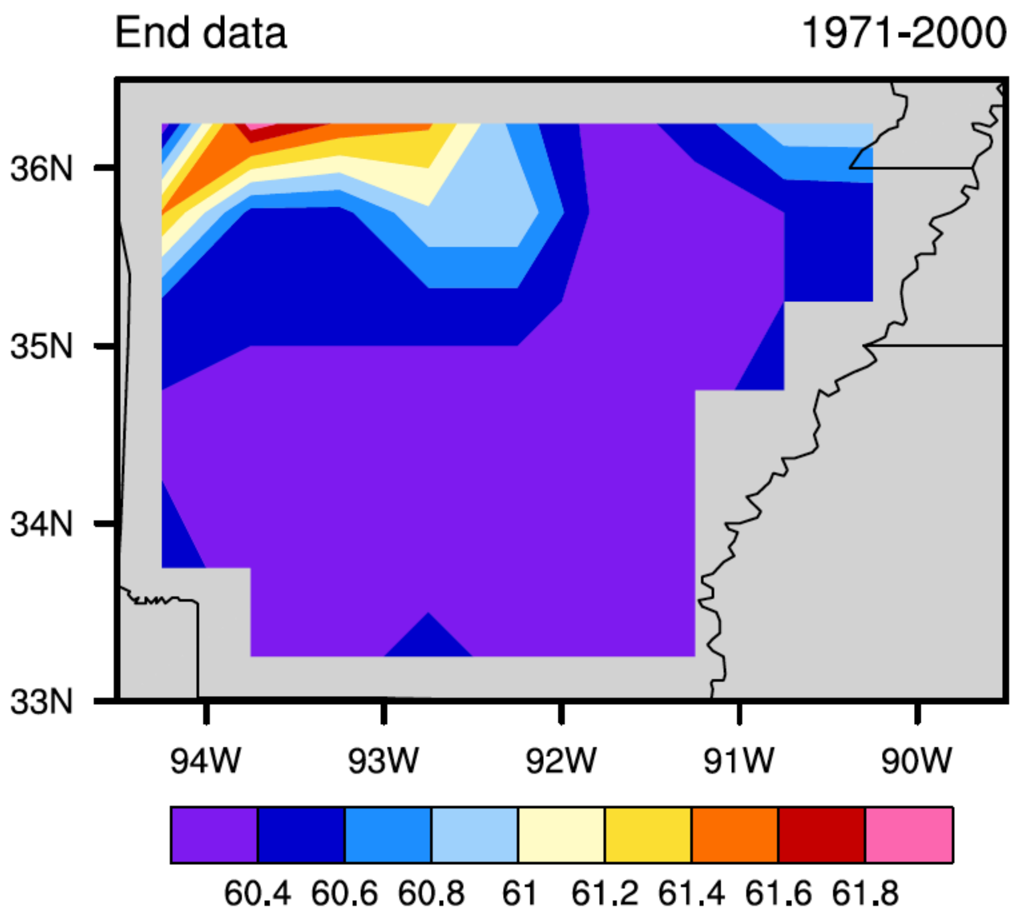


Figure 2.3.9 Average end date of the winter season for Arkansas during 1971-2000. The unit is day of year

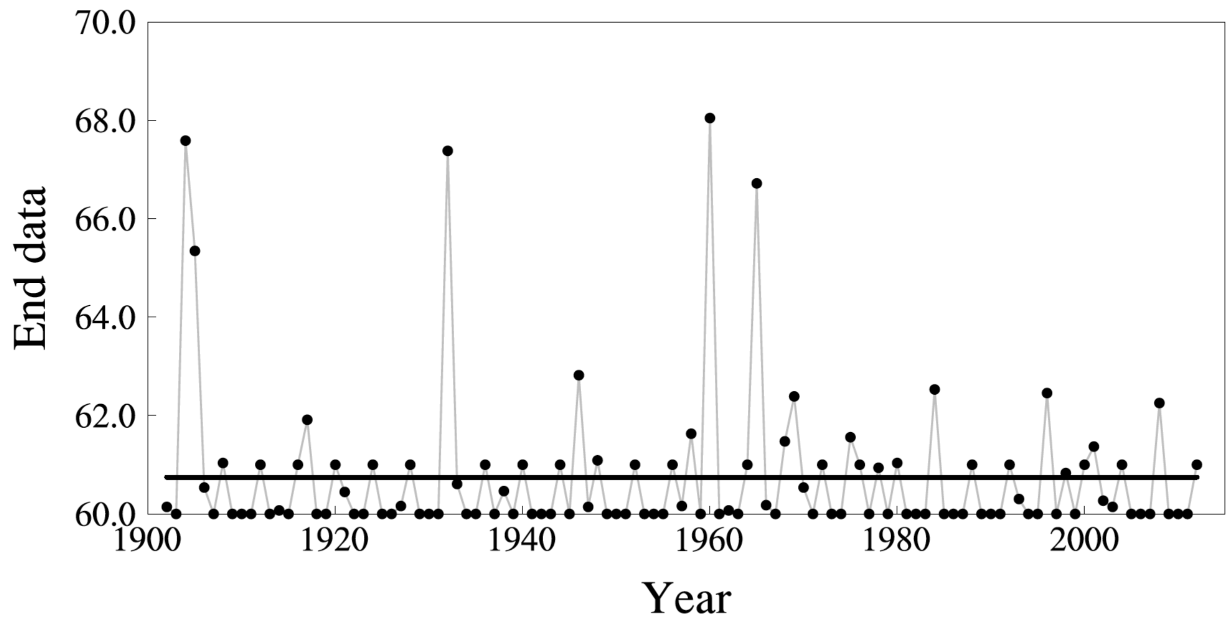


Figure 2.3.10 Time series plot of average end date of the winter season for Arkansas. The black line represents the trend from 1901 to 2012

As seen in figure 2.3.10 above, the state averaged end of the winter season for the state of Arkansas occurs around March 1st during the studied period. In summary the trend is not significant for the end of the winter season but there are a few outliers, especially in northern Arkansas with late season snowfalls. On average the AWSSI stops accumulating points around the first week of March for most of the state.

Putting together the start and end dates for the winter season we can look at the overall winter season length. Figure 2.3.11 suggested that the spatial distribution of the length of the winter season stays nearly consistent with the results for the start and end dates, where the further northern areas of the state experience a slightly longer winter season on average. The winter season from the southern end of the state to the northern end of the state does vary like previously stated but it is not a significant amount of difference on about three to four days on average between 1971 to 2000.

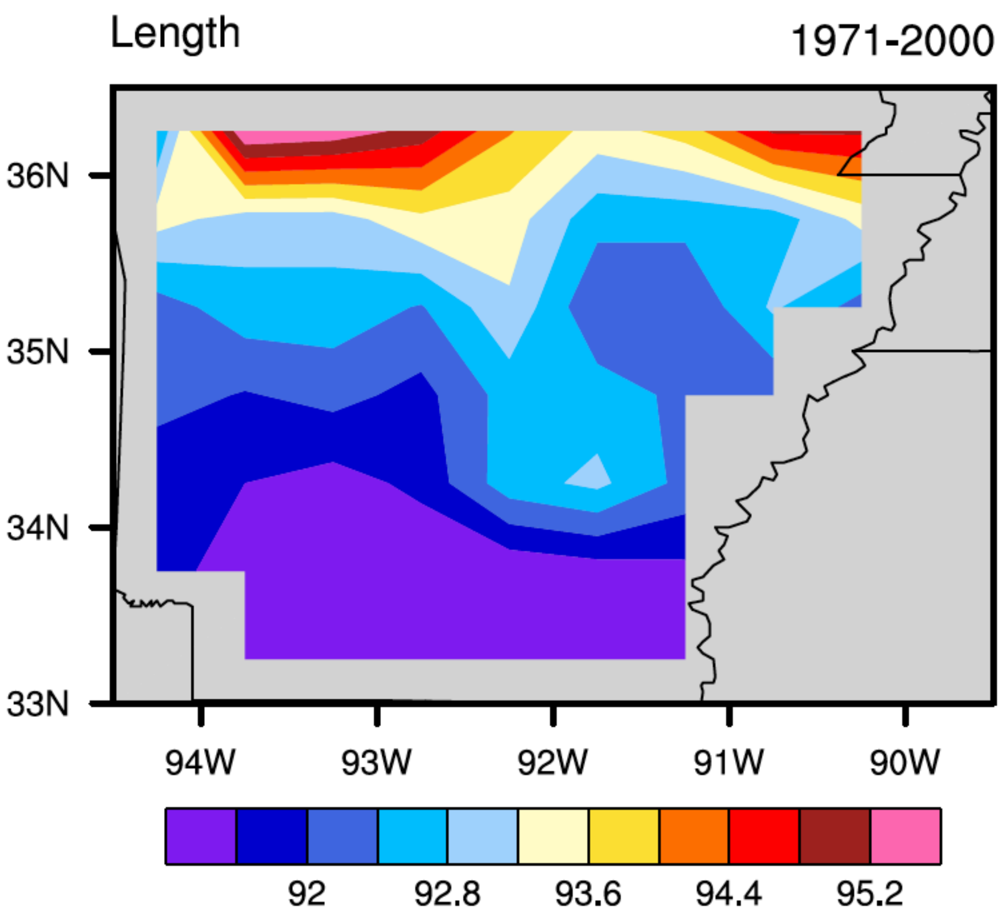


Figure 2.3.11 Average length of winter season represented by day of the year for Arkansas averaged during 1971-2000 (Units in number of days with 92 days being the standard Dec.1 to March 1)

Figure 2.3.12 shows the temporal variations of the state averaged length of the winter season. Again, there is no notable long-term trend in the length of winter season during 1901 to 2012. However, there is tendency that the winter season became shorter since 1960s.

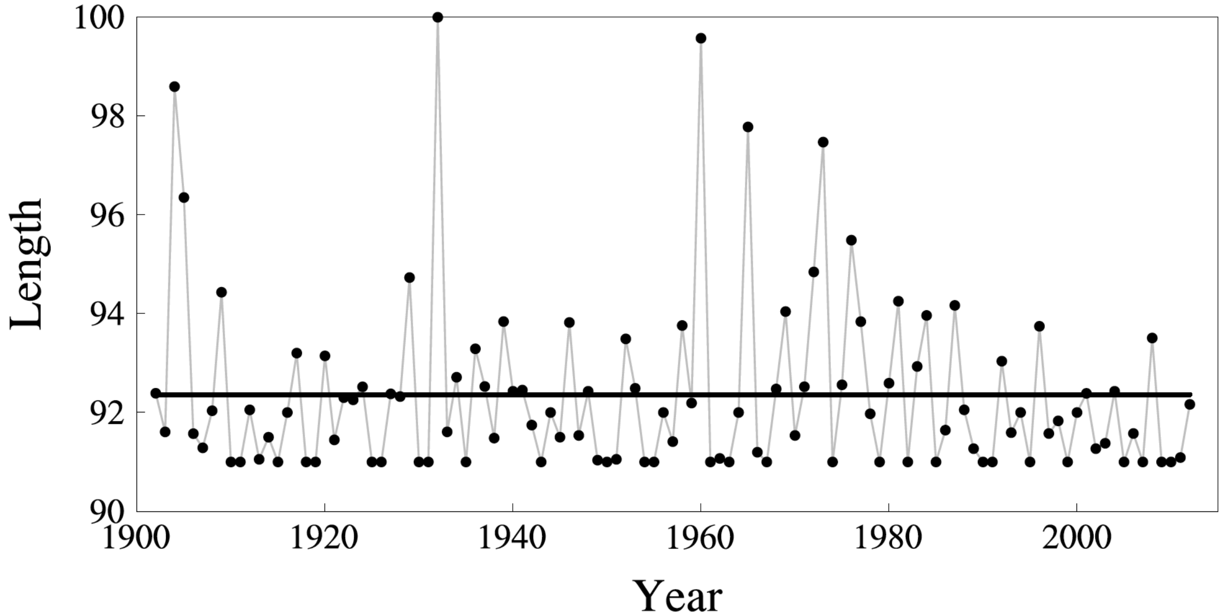


Figure 2.3.12 Time series plot of average yearly length of the winter season for Arkansas. The black line represents the trend from 1901 to 2012

The AWSSI combines the temperature, snowfall, and snow depth to quantify the severity of a winter season. Therefore, the AWSSI can be decomposed into temperature-based and snow-based components, termed as AWSSI-temperature and AWSSI-snow. Specifically, the AWSSI-temperature using only temperature scores (Table 2.1) to quantify the severity of winter. Similarly, the AWSSI-snow only accumulates the snowfall and snow depth scores. Figure 2.3.13 shows the average AWSSI score based on temperature. The AWSSI-temp in general increase with latitude and altitude consistent with the long-term mean winter temperature. The AWSSI-temper score in the southwest AR is less than 50, while it is over 120 in the northwest AR.

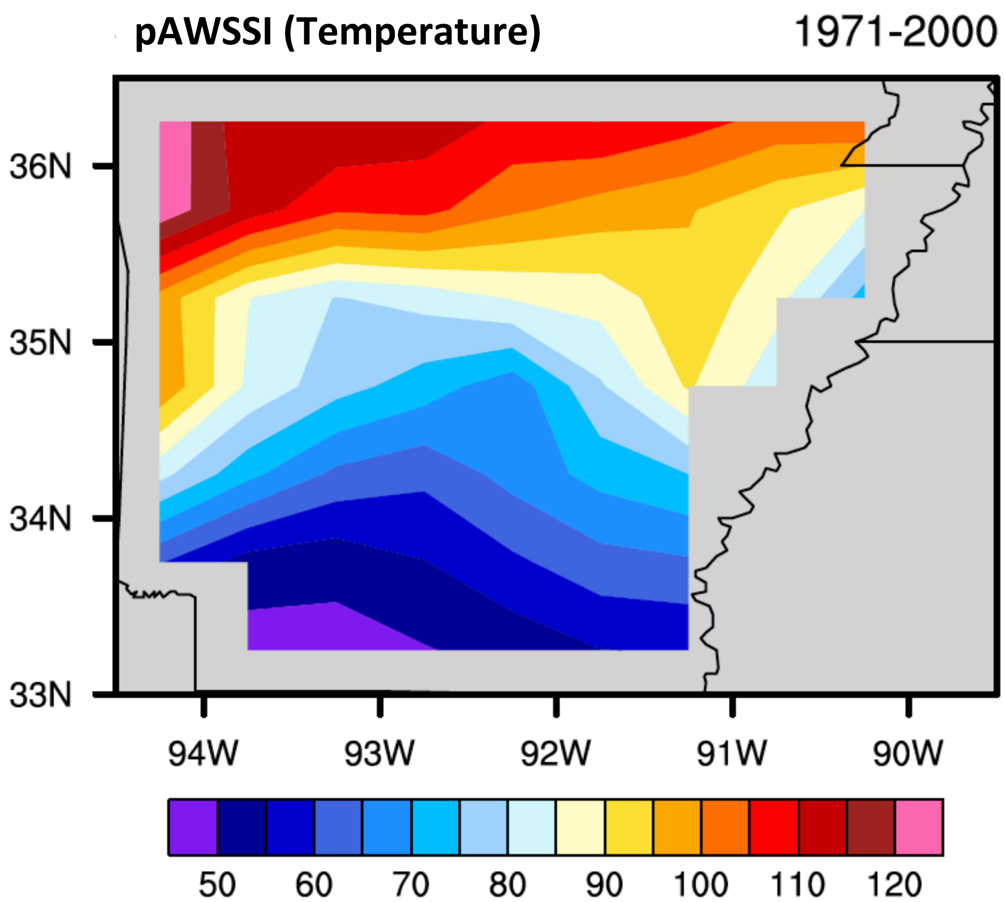


Figure 2.3.13 Spatial distribution of average pAWSSI using temperature as the only variable for Arkansas during 1971-2000

Figure 2.3.14 shows the temporal variations of AWSSI-temperature during 1901-2012. The notable peaks in AWSSI-Temperature scores appeared in the late 1970s and early 1980s, consistent with state-averaged pAWSSI (Figure 2.3.6). Overall, the temporal distribution has been trending with lower AWSSI scores, especially after late 1970s, suggesting that warmer than average winters are becoming more prevalent in recent decades.

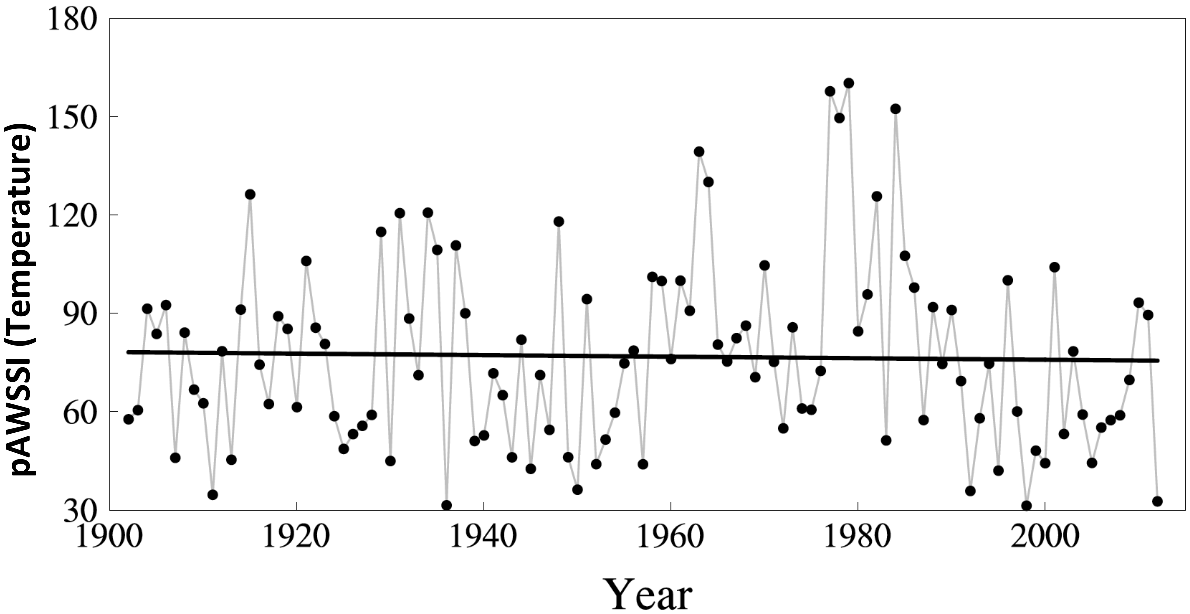


Figure 2.3.14 Temporal variations of pAWSSI-temperature averaged over Arkansas. The black line represents the trend from 1901 to 2012.

On average most of the state of Arkansas has minimal snowfall during winter. The higher amounts usually falling across northern Arkansas were anywhere from 4 to 12 inches of snowfall occur in winter. In figure 2.3.15 below we can see the spatial distribution of AWSSI-Snow is higher in the far northern sections of the state, which average score between 14 and 20. Compared to the southern end of the state which averages a score of less than 6 for AWSSI-Snow. On average in the northern third of the states experiences the higher snowfall totals which align with the spatial distribution seen during 1971-2000. Comparing to the long-term mean AWSSI-temperature (Figure 2.3.13), the AWSSI-snow is much smaller, suggesting that the pAWSSI in AR is mostly contributed by temperature.

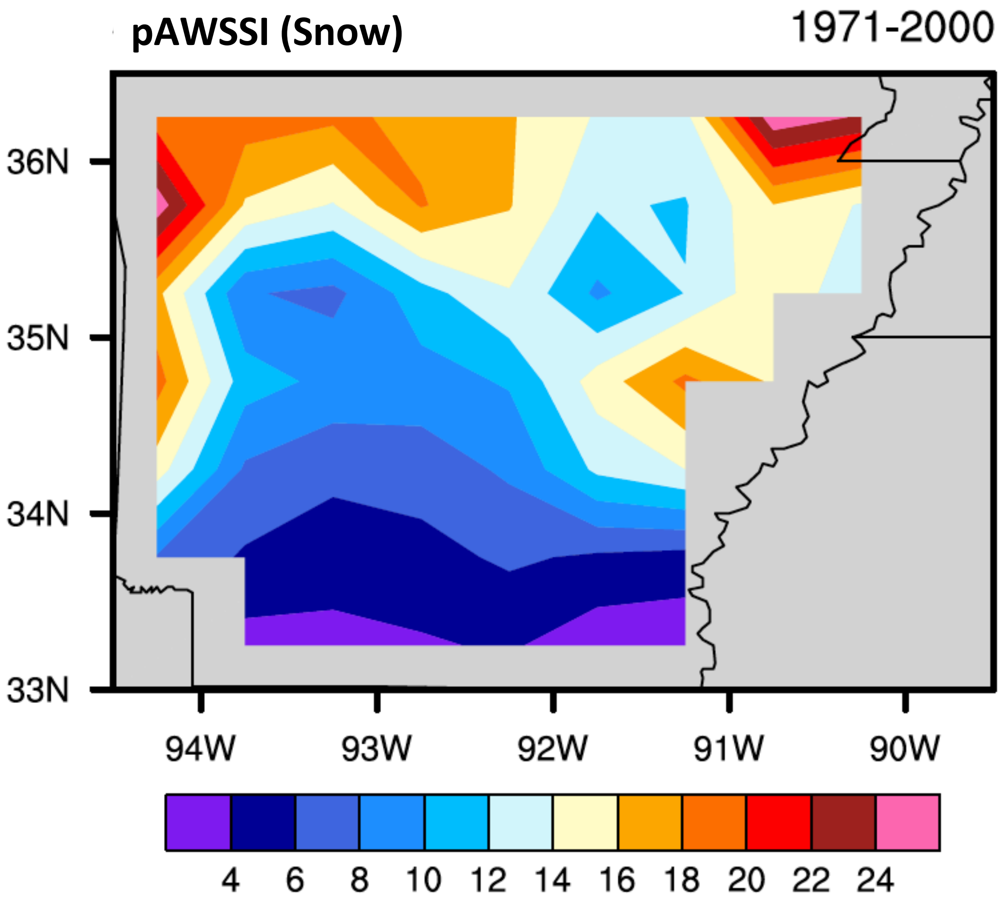


Figure 2.3.15 Spatial distribution of average pAWSSI using snowfall as the only variable for Arkansas between 1971 and 2000

Figure 2.3.16 shows the temporal variations of AWSSI-snow. Total AWSSI-snow scores usually range between 5 and 10 on average, but the winters of the late 1970s experienced abnormally high amount of snowfall across most of Arkansas. There is a visible decrease in the AWSSI snow scores, especially since late 1970s.

The temperature component of AWSSI also appears to have stronger interannual variability as well as a more defined long-term trend compared to that of AWSSI-snow (Figures 2.3.14, 2.3.16). It can be concluded that the temperature component dominates the total AWSSI variations than snowfall. This is the case most likely because snowfall in the state of Arkansas can be almost a nonfactor, especially for the southern half of the state. On the other hand, even though snowfall is not a major factor for a large portion of the state, temperature variability is still prevalent and contributes in a more significant way to the total AWSSI scores on a yearly basis.

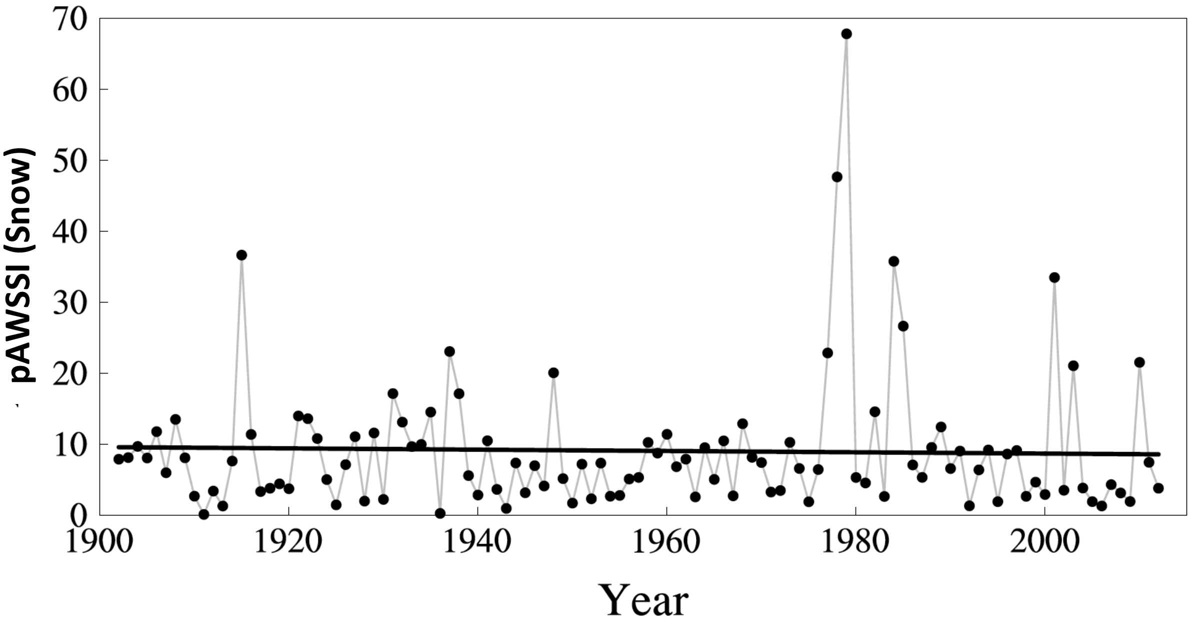


Figure 2.3.16 Time series plot of average pAWSSI using snowfall as the variable for Arkansas. The black line represents the trend from 1901 to 2012.

The dominance of temperature on pAWSSI in AR is further supported by the consistent out-of-phase variations in pAWSSI and winter temperature during 1901-2012 (Figure 2.3.17). The colder the winter temperature, the higher the pAWSSI. The correlation between the two timeseries is as high as -0.61 ($p<0.01$), which indicates that the changes in pAWSSI are largely driven by air temperature. Additionally, the less harsh winters since late 1970s are associated by warming winter.

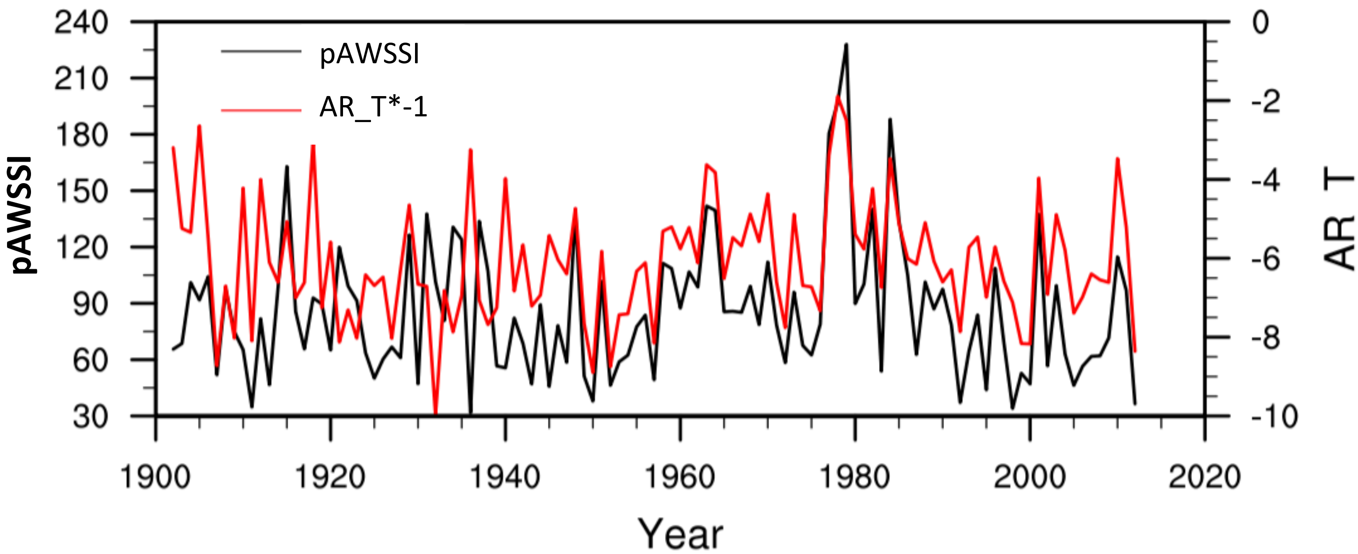


Figure 2.3.17 Temporal variations of the stated averaged pAWSSI (black line) and winter temperature (red line) in AR during 1901-2012. The unit of temperature is degrees Celsius. Note that the winter temperature was timed by -1 for better comparison with the pAWSSI

2.3.4 Influence of Atmospheric Modes on pAWSSI in Arkansas

To understand the physical mechanisms that influence the winter severity in Arkansas, the state-averaged pAWSSI is correlated to several large-scale atmospheric and oceanic indicators. The correlation between pAWSSI and winter NAO is -0.51, significant at 95% confidence level. The strong links are reflected by the close temporal variations of the two timeseries (Figures 2.3.18). On interannual time scale, the winters with higher AWSSI scores are usually associated with negative NAO phases. Additionally, the long-duration harsher winters in the 1960s and during 1976-1985 are also linked to negative NAO phases. The milder winters during 1990s and 2000s are associated with positive NAO phases. The NAO positive phases are associated positive pressure in the middle and low latitude North Atlantic (Liu et al., 2021). The positive anomalous pressure extended westward to influence the southeast United States and the Gulf of Mexico. The higher-than-normal pressure in these regions could courage more warm air mass to influence the southeast United States (including Arkansas), encouraging milder winters in AR. Additionally, the higher-than-normal pressure prohibits upward movement and thereby leads to less cloud development and more solar radiation to reach the ground and warmer temperature.

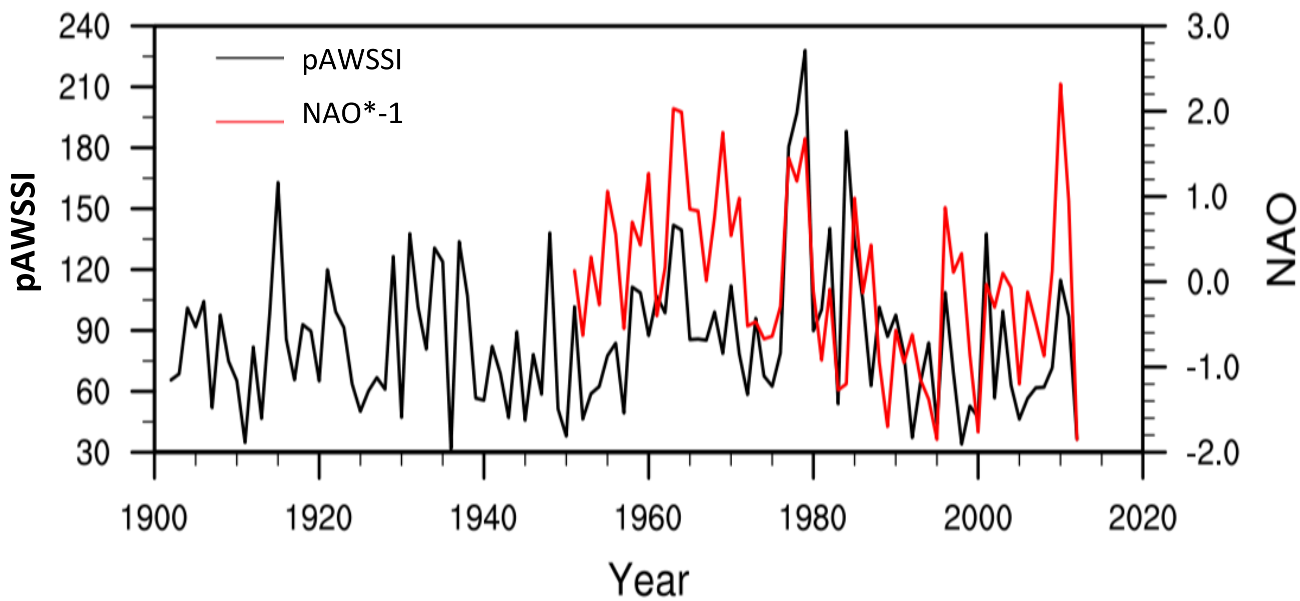


Figure 2.3.18. Temporal variations of the state-averaged pAWSSI in Arkansas and the winter NAO. Note that the NAO was timed by -1 for better comparison with the pAWSSI.

The pAWSSI is also significantly correlated with PDO (CC=0.33, p=0.05) during 1948-2012. As shown in Figure 2.3.19, the year-to-year variations in PDO is closely linked to pAWSSI. However, the link between PDO and pAWSSI is weak during the recent two decades, suggested that the impacts of PDO on winter severity in Arkansas may change on decadal time scales. The PDO is associated with higher-than-normal pressure in the northwestern North America and below normal pressure in the southeastern United States (Liu et al., 2021). This pressure pattern favors stronger north-south air movement and may transport more cold air mass from the Canada to the central and southern United States, thereby leads to colder Arkansas. It worth noting that the links between pAWSSI and ENSO is rather weak, possibly because the

ENSO has weak impact on the winter climate the central United States, albeit it has strong impacts on the northwest and southeast United States.

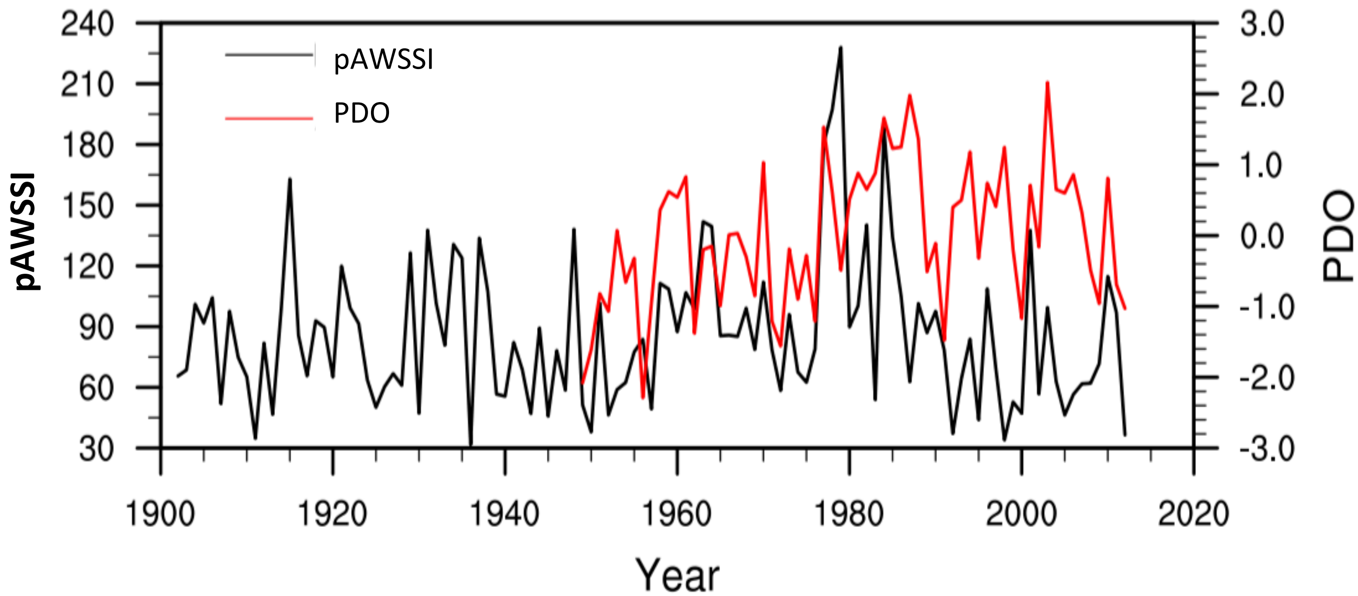


Figure 2.3.19 Temporal variations of the state averaged pAWSSI and winter PDO.

2.4 Conclusions

The chapter examined the winter severity in Arkansas based on observational data and the newly developed accumulated winter season severity index. The long-term mean AWSSI suggested more harsher winter in the northern and northwestern of the state. The temporal variations of the state averaged AWSSI suggest weak trend before middle 1970s followed by notable decreasing AWSSI scores, suggesting less harsher winters in recent decades. However, the start, end, and length of winter season in AR show weak spatial and temporal variations.

The long-term mean pAWSSI and its trend are largely influenced by winter temperature. The decreasing pAWSSI (less cold winter) is associated with warming temperature, especially in the recent several decades. The temporal variations of pAWSSI are also influenced by large-scale atmospheric and oceanic indices, such as the NAO and PDO.

Chapter 3: Projected Changes in Arkansas Winter Severity

Abstract

In this chapter I will look at how the pAWSSI and its individual parameters will be affected in a future warmer world. Specifically, the pAWSSI in 2071-2100 simulated by 20 CMIP5 models was compared to that during 1971-2000. It was found that under the RCP 8.5 scenario, the winter severity measured by using pAWSSI is projected to gradually decrease towards the end of the century. This will lead to warmer temperatures and less snowfall on average for the state of Arkansas. The percentage change and decrease in winter severity does range throughout the state, with parts of northern Arkansas experiencing the most drastic changes since these areas have historically had the more severe winter seasons.

3.1 Introduction

Changes in climate and extremes during the past 50-100 years have already adversely affected the ecosystems, water resources and food supply (NCA, 2014). These impacts vary by regions (NCA, 2014). These impacts are projected to be more pronounced in a future warmer climate (i.e., Feng et al., 2017, Mirek et al., 2019; NCA, 2014). The state of Arkansas is one of the regions prone to weather and climate extremes (Smith and Katz, 2013). The temperature and frequency of weather extremes in Arkansas and neighboring regions are also projected to increase notably in the future (NCA, 2014), which could add more hardship in managing the agriculture and ecosystems in the states (i.e., Magugu et al., 2018; Donahou, 2018).

Changing in climate also influences the winter weather extremes (i.e., Liu et al., 2021). In Chapter 2, the spatial and temporal variations of winter severity in AR were examined. It was found that the state experienced less harsh winters in recent decades following the warming in winter temperature since late 1970s. How could the winter severity change in the future in Arkansas? This chapter aims to address this question by examine the model simulations during 2006-2100 in more than 20 models participated in the Climate Model Intercomparison Project Phase 5 (CMIP5).

3.2 Data

To examine the future winter severity in Arkansas, the daily temperature and precipitation in more than 20 CMIP5 models were used in this study. The climate models used include ACCESS1-0, GFDL-CM3, MPI-ESM-LR, BNU-ESM, GFDL-ESM2G, MPI-ESM-MR, CCSM4, GFDL-ESM2M, MRI-CGCM3, CESM1-BGC, IPSL-CM5A-LR, CNRM-CM5, IPSL-CM5A-MR, CSIRO-Mk3-6-0, MIROC-ESM, bcc-csm1-1 CanESM2, MIROC5, NorESM1-M, and inmcm4. Model simulations with observed anthropogenic and natural forcing during 1950-2005 and with 21st century changes in greenhouse gases and aerosol under the business as usual scenario (RCP8.5) during 2006-2100 (Taylor et al., 2012) were analyzed. Previous evaluations (i.e., IPCC 2017; Feng et al., 2014) suggested that these models can reasonably simulate the temperature and precipitation variations on global and regional scales.

Because the models differed in spatial resolutions and physics, the daily maximum and minimum temperature and daily total precipitation from these climate models during 1950-2100 were statistically downscale to 0.25-degree resolution by NASA (2015). These data were used to calculate pAWSSI along with temperature and snow based pAWSSI, as well as the start, end, and length of the winter season. The algorithms to estimate snowfall, snow depth and pAWSSI scores are the same as in Chapter 2. To quantify the uncertainties in the climate models, the standard deviation of the projected changes in winter severity and related indices among the 20 models was also calculated.

To evaluate the projected changes in winter severity, the average pAWSSI and related indices during 2071-2100 under RCP8.5 scenario were calculated. For comparison, the average conditions during 1971-2000 (termed as present-day) with observed anthropogenic and natural forcing were also calculated. The ensemble of the 20 CMIP5 models were analyzed. The differences between the two periods reflect the projected changes in winter severity by the end of this century comparing to the present-day conditions. To evaluate the temporal changes in winter severity, the state-averaged pAWSSI and related indices from 1950-2005 with observed anthropogenic and natural forcing and from 2006-2100 under RCP8.5 were calculated. The state-averaged pAWSSI based on GLDAS data during 1901-2012 was also calculated to evaluate the quality of the model simulations. To quantify the uncertainties in the model projections, the one standard deviation of the 20-model simulations was calculated.

3.3 Projected changes in pAWSSI

Figure 3.1.1b shows the averaged pAWSSI for the years of 2071-2100 under RCP8.5 scenario. Compared to the present-day condition (Figure 3.1.1a), the pAWSSI in Arkansas is projected to experience a significant decrease. One example is for the Northwestern parts of the state. The average AWSSI values in the present day is about 120-140 or higher. The number is projected to decrease to be less than 60 by the end of this century, which is more than 60% less comparing to the present day. The most notable changes appear in the south and southwest AR, where the pAWSSI is projected to decrease from 50-60 during 1971-2000 to below 20 during 2071-2100, which means there are barely any significant winter weather in these regions by the end of this century. In general, the pAWSSI is projected to decrease 60-70% during 2071-2100 under the business-as-usual scenario (Figure 3.1.1c).

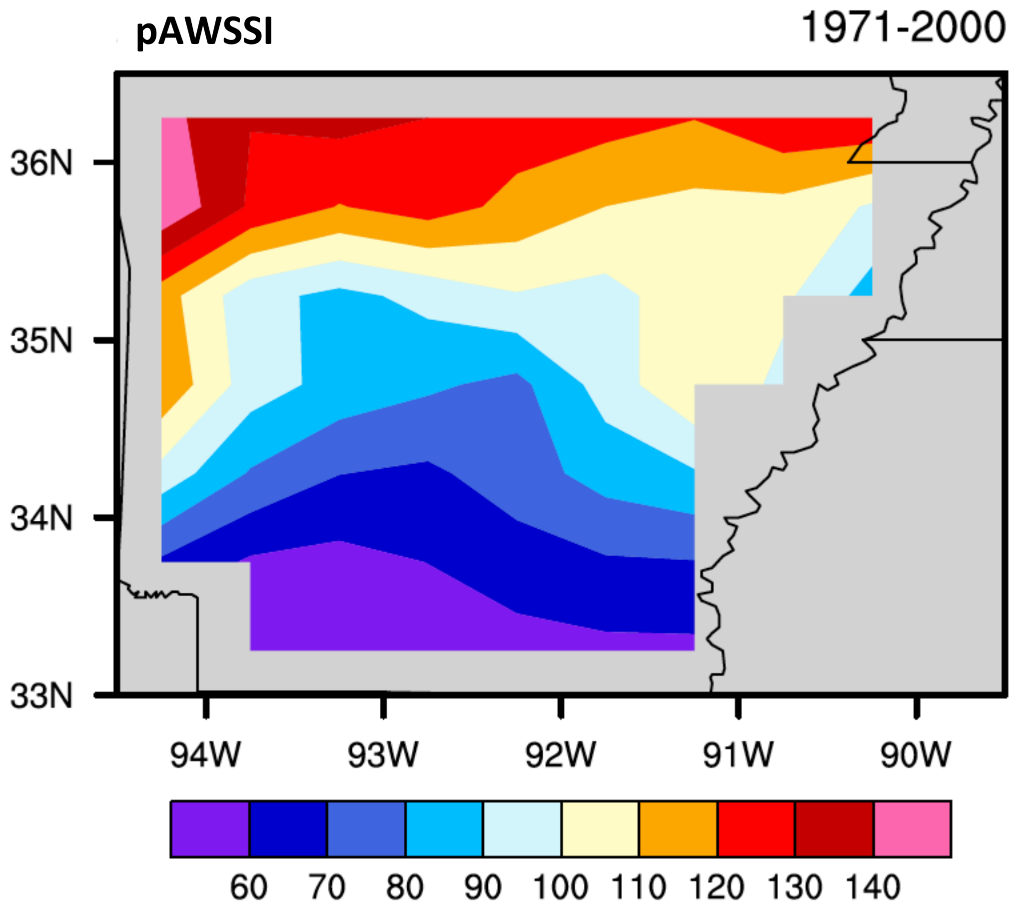


Figure 3.1.1 (a) *Spatial distribution of the average pAWSSI during (a) 1971-2000 and (b) 2071-2100 under the RCP8.5 scenario. (c) shows the projected changes in pAWSSI (%) during 2071-2100 relative to 1971-2000. The results shown are the ensembles of 20 CMIP5 models.*

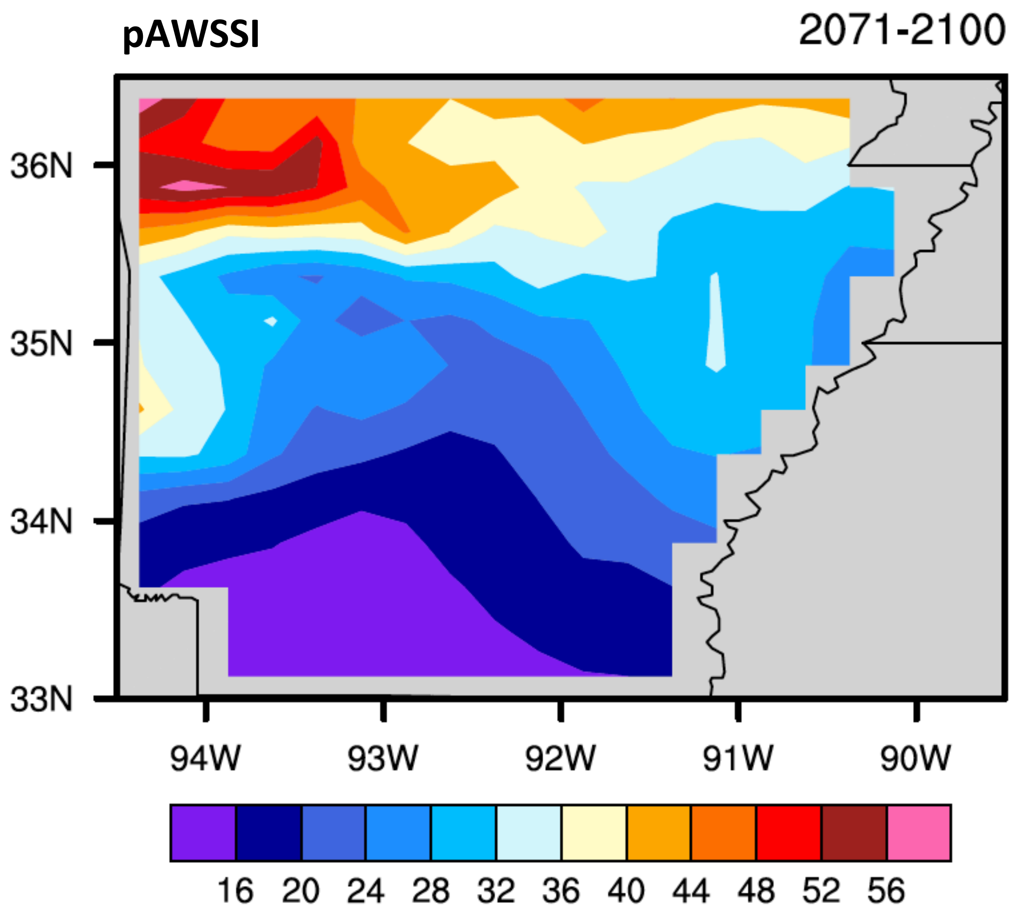


Figure 3.1.1 (b) *Projected average pAWSSI scores for Arkansas using RCP 8.5 for years 2071-2100.*

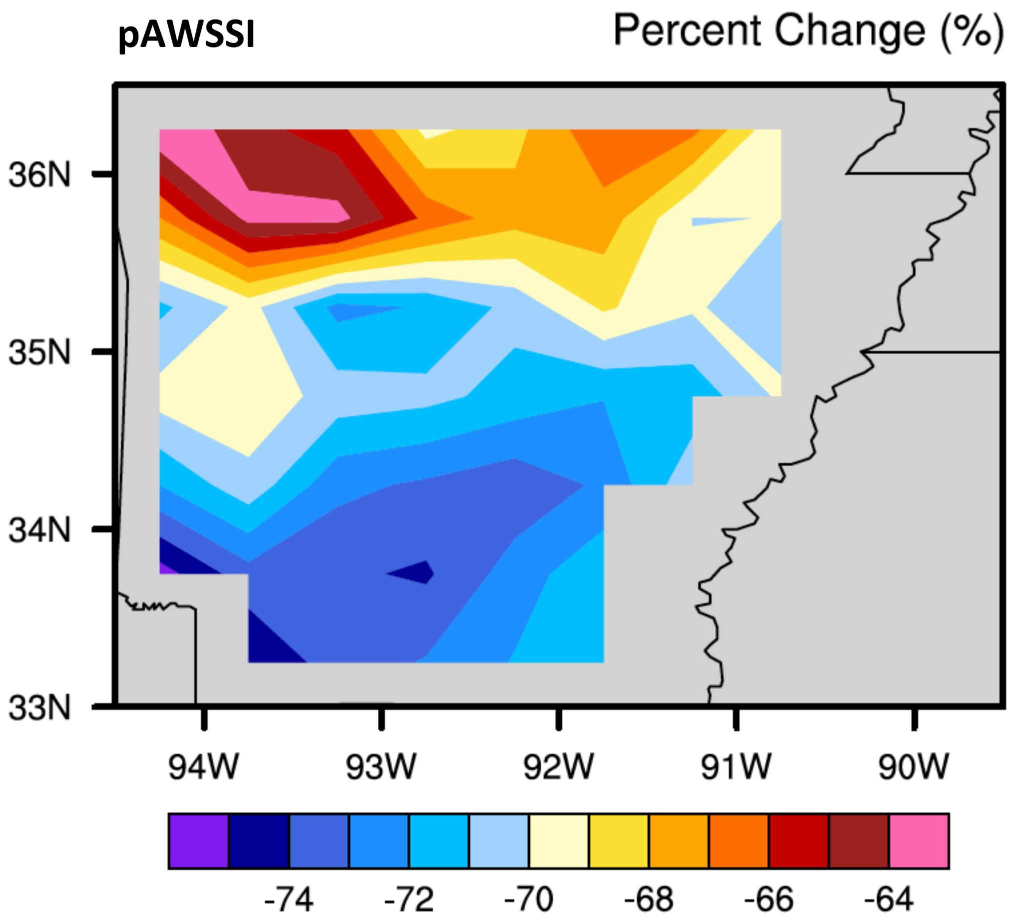


Figure 3.1.1 (c) *Projected average percent change of pAWSSI scores for Arkansas using RCP 8.5 comparing percent change between 1971-2000 and 2071-2100 pAWSSI averages.*

To evaluate the temporal changes in pAWSSI, Figure 3.1.2 shows the temporal variations of the state-averaged pAWSSI from 1950-2100. Comparing to the pAWSSI based on GLDAS data, the ensemble of the 20 CMIP5 models show similar long-term averaged and trend in pAWSSI during 1950-2012, suggesting that the models did a reasonable job in simulating the temporal variations of pAWSSI. The models projected accelerating decreasing trend in pAWSSI from 2006-2100, suggesting that the projected climate changes can cause pronounced decrease in winter severity. By the end of this century, the state-averaged pAWSSI is projected to be below 30, suggesting that the harsh winters in AR will become much less under the business-as-usual scenario. It worth mention that the model uncertainties of pAWSSI become smaller during 2006-2100. This result is different from many other modeled climate variables (i.e., temperature and precipitation) which show increasing model uncertainties in a future warmer world (i.e., Feng et al., 2014, NCA, 2014). The possible reason is that the winter in AR is in general mild, and the models projected reducing harsh winters under the RCP8.5. Less severe winters lead to lower pAWSSI scores.

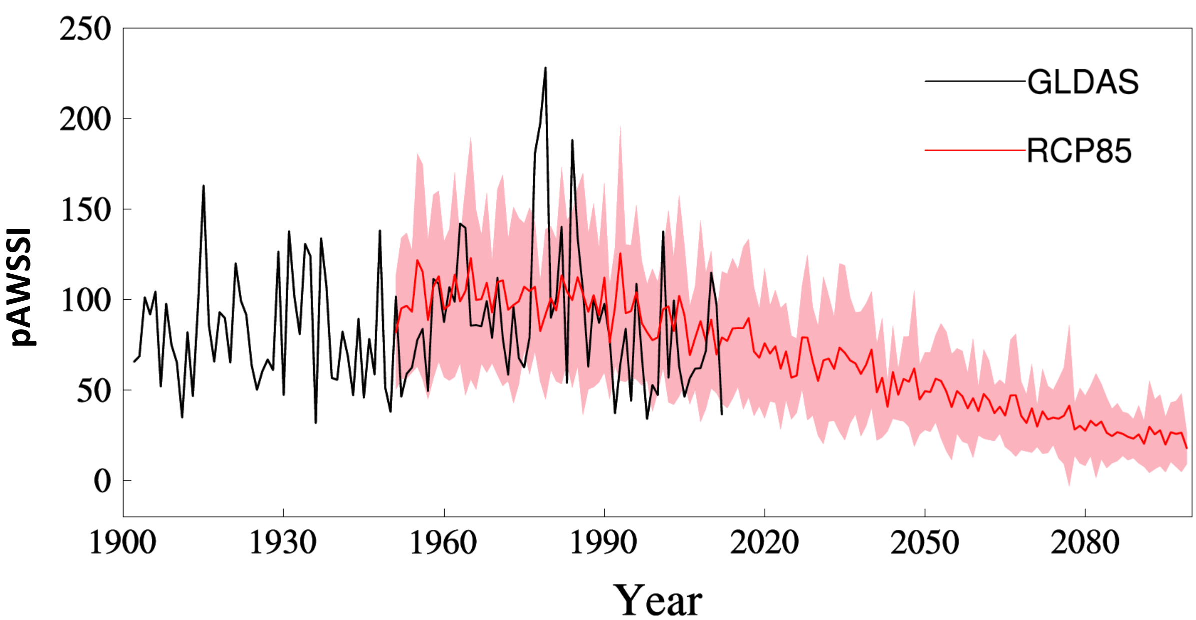


Figure 3.1.2 *Time series of the state-averaged pAWSSI scores for Arkansas. Black line is based on GLDAS during 1901-2012, while red line is based on the ensemble of the 20 CMIP5 models during 1950-2100. The pink shading denotes one standard deviation of the 20 CMIP5 model simulations.*

3.4 Projected changes of the Winter Severity using AWSSI's parameters

As discussed above, the pAWSSI averages for Arkansas are projected to trend down during this century. To get a closer and more detailed look of the projected changes in winter severity, I also looked at the start, end, and length of the winter season, along with temperature and snow based pAWSSI.

The spatial distribution of the averaged start date of winter season during 2071-2100 under the RCP 8.5 scenario (Figure 3.2.1b) is like the averages of 1971 to 2012 (Figure 3.2.1a). This result confirms that the start of winter remains nearly constant in Arkansas (i.e., December 1st). The greatest changes in the starting date is indiscernible (2 days or less, Figure 3.2.1c). This result suggested that AR is rarely affected by below 32°F daytime temperature or greater than 0.1 in of snow before December 1st (see Chapter 2 for the definition of winter season).

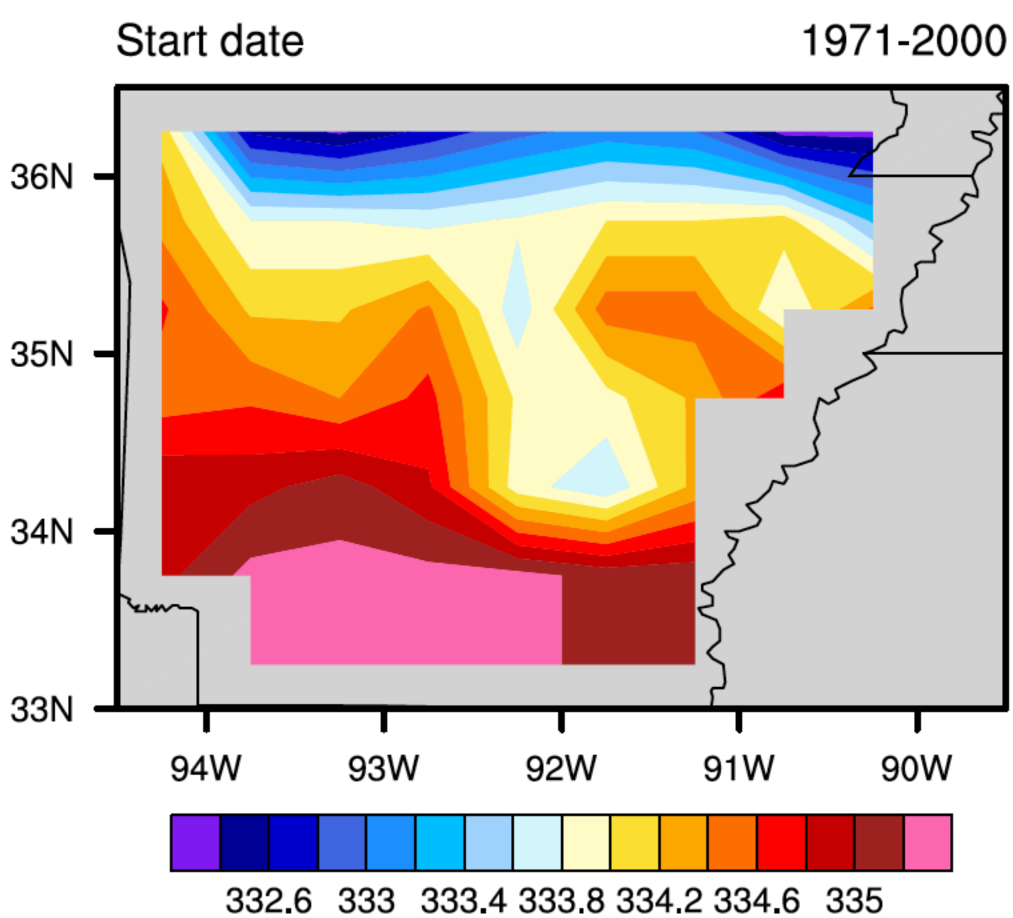


Figure 3.2.1 (a) *Spatial distribution of the average starting date of winter during (a) 1971-2000 and (b) 2071-2100 under the RCP8.5 scenario. (c) shows the projected changes in the starting date (days) during 2071-2100 relative to 1971-2000. The results shown are the ensembles of 20 CMIP5 models.*

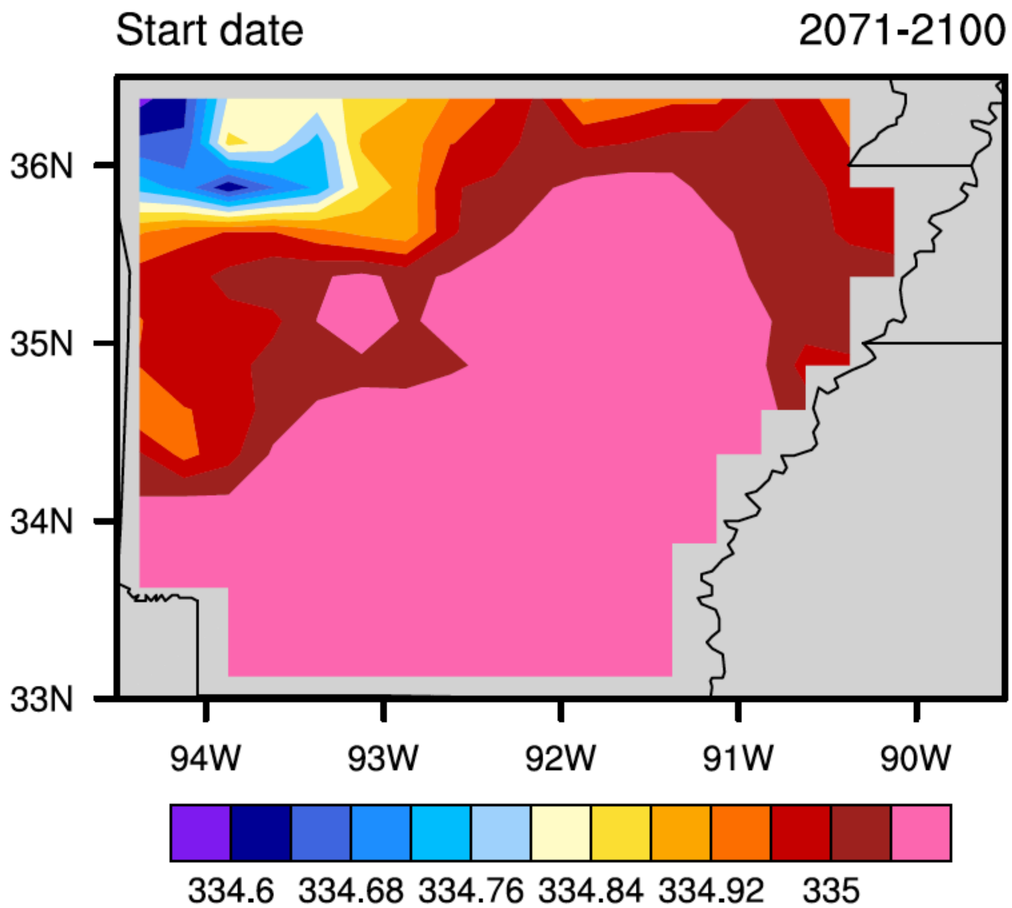


Figure 3.2.1 (b) *Projected average winter season start times for Arkansas using RCP 8.5 for years 2071-2100. The unit of the values are in days of the year.*

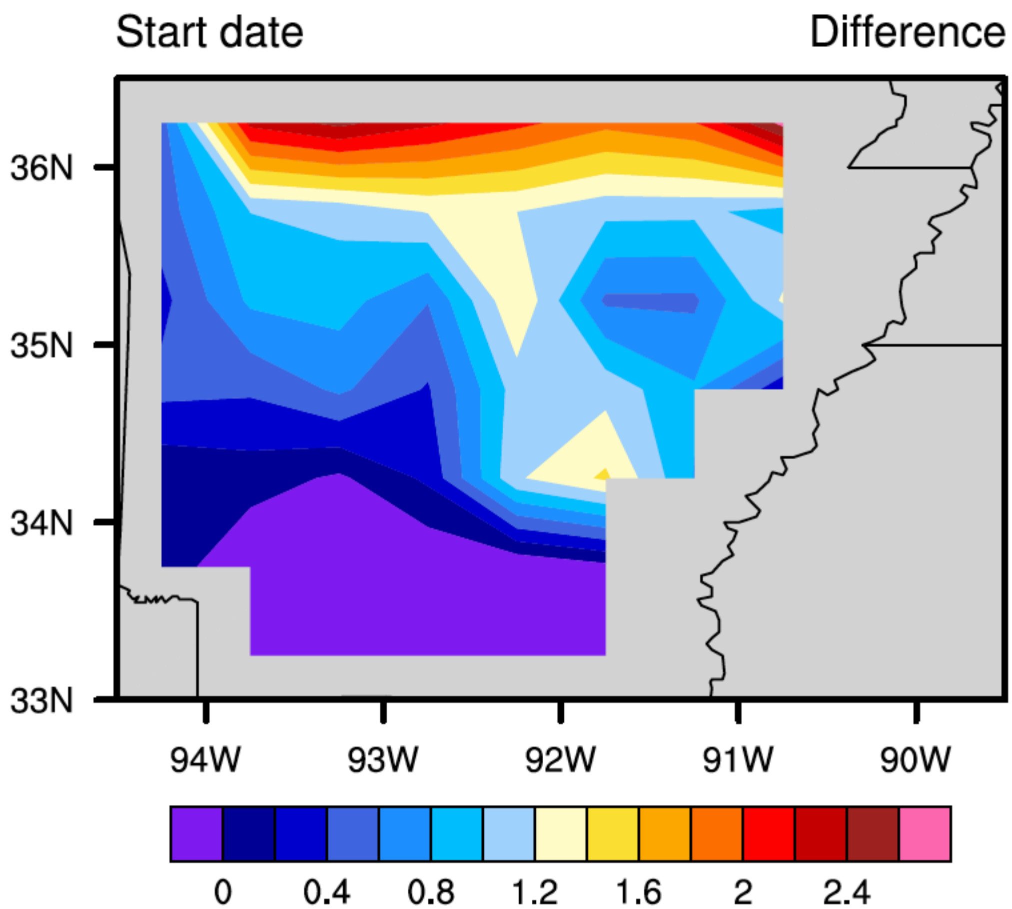


Figure 3.2.1 (c) *Projected average change of the winter start date for Arkansas using RCP 8.5 comparing change in number of days between 1971-2000 and 2071-2100 AWSSI averages.*

The temporal variations of start of winter also did not experience much change (3.2.2). The winter season for most of Arkansas starts on December 1st, which is late compared to areas in northern parts of the country.

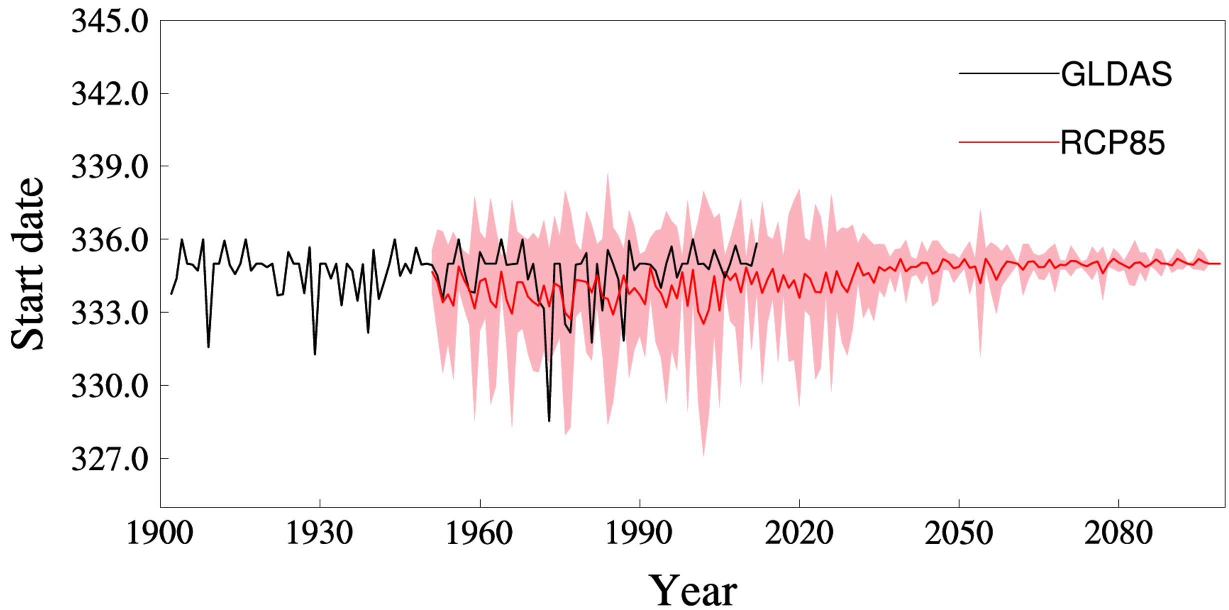


Figure 3.2.2 *Time series of the state-averaged pAWSSI scores for Arkansas. Black line is based on GLDAS during 1901-2012, while red line is based on the ensemble of the 20 CMIP5 models during 1950-2100. The pink shading denotes one standard deviation of the 20 CMIP5 model simulations.*

The spatial distribution for the end of the winter season in the RCP 8.5 scenario (Figure 3.2.3b) shows a similar pattern to the averages from 1971 to 2012 with no significant changes (Figure 3.2.3a). This can be explained by the default end of winter which is March 1st or day 61 of the year. This default date of March 1st is giving when the rest of the criteria for the cessation of the winter season are not met. Areas further to the northern United States experience an end of winter later in March or into April because the criteria continue to be met, such as high temperatures below 0 degrees C, along with the other criteria previously discussed (see the definition of winter in Chapter 2). With Arkansas not typically experiencing harsh winters the default end of winter is usually enacted. The projected changes in the end date is also indiscernible (2 days or less, Figure 3.2.3c).

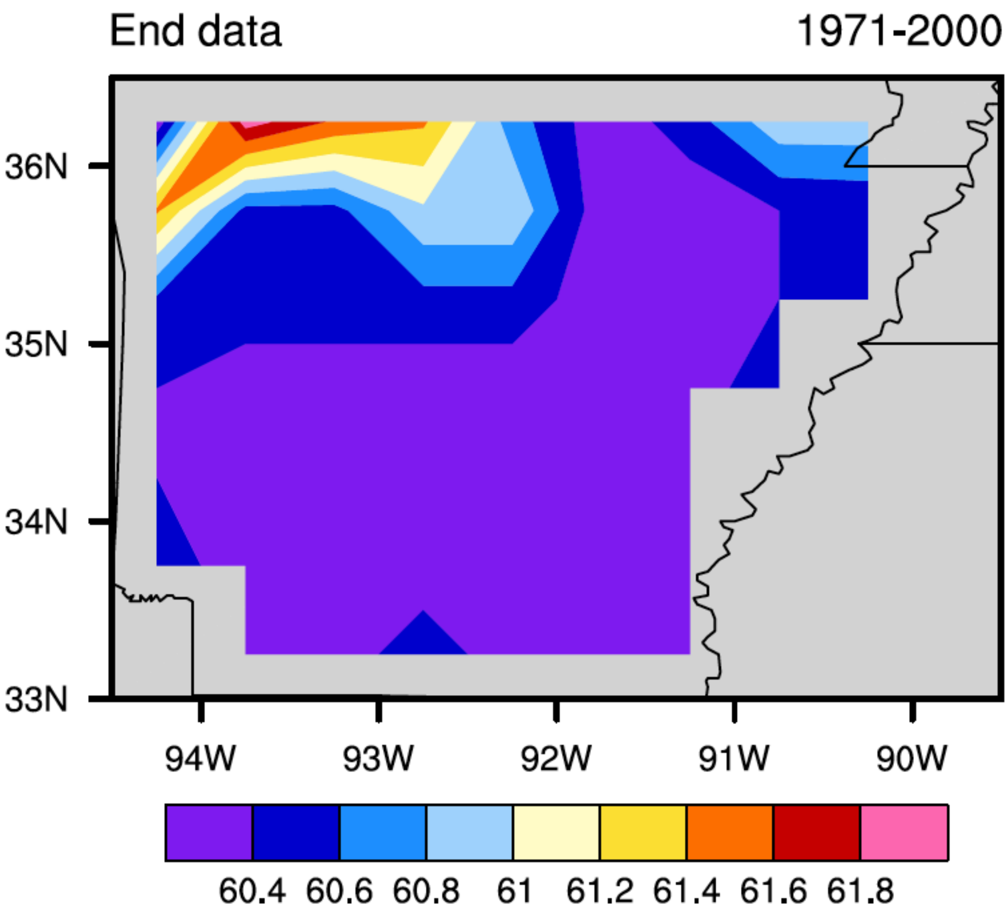


Figure 3.2.3 (a) *Spatial distribution of the average end date of winter during (a) 1971-2000 and (b) 2071-2100 under the RCP8.5 scenario. (c) shows the projected changes in the end date (days) during 2071-2100 relative to 1971-2000. The results shown are the ensembles of 20 CMIP5 models.*

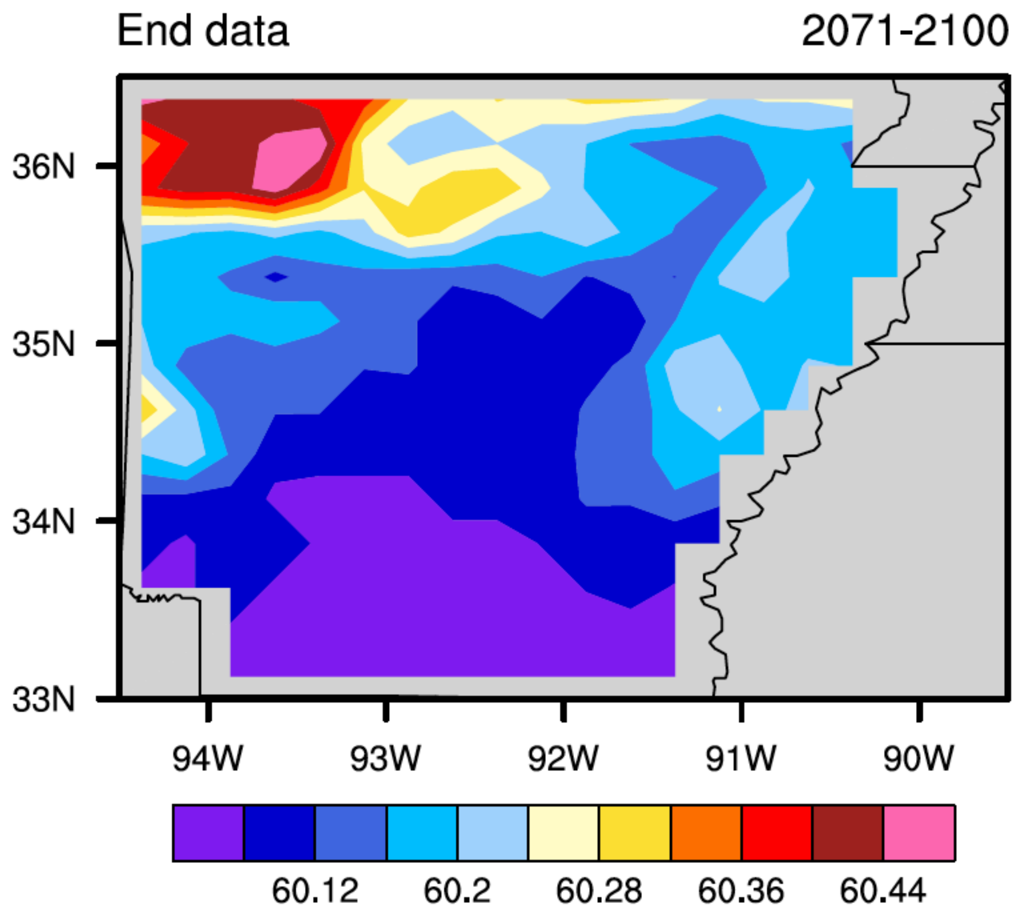


Figure 3.2.3 (b) *Projected average winter season end times for Arkansas using RCP 8.5 for years 2071-2100. The unit of the values are in days of the year.*

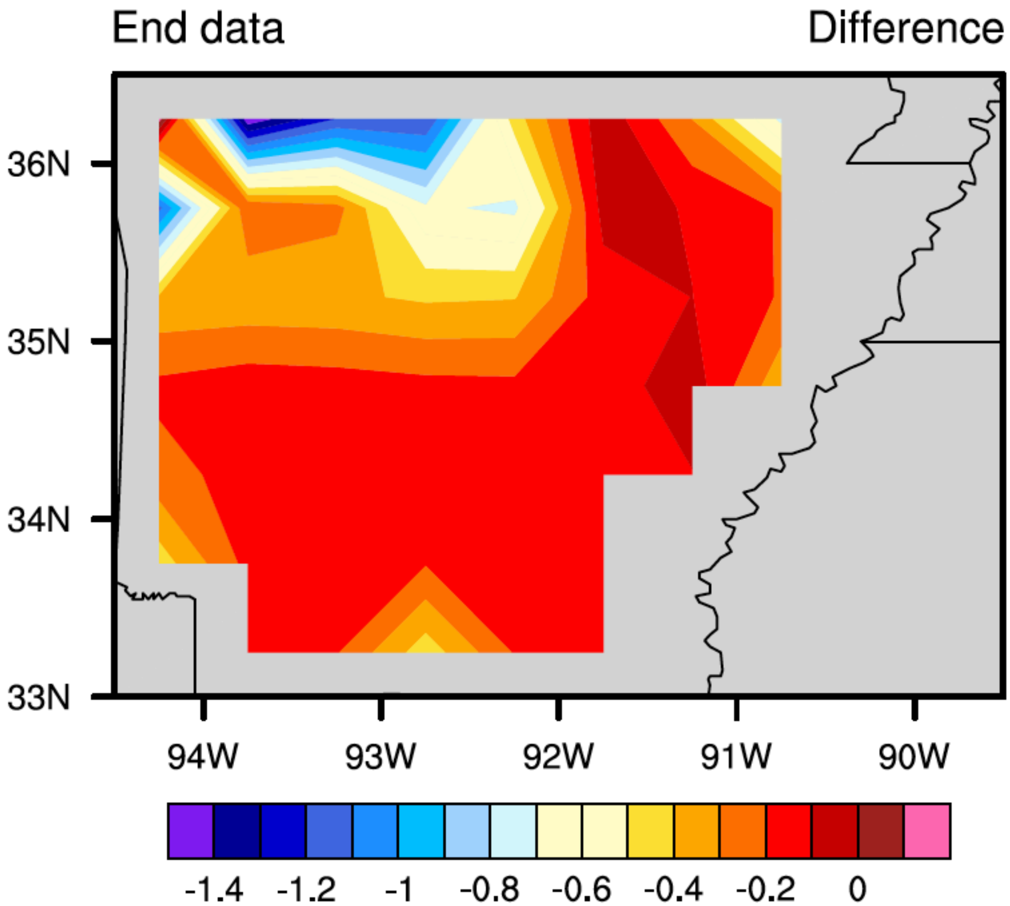


Figure 3.2.3 (c) *Projected average change of the winter end date for Arkansas using RCP 8.5 comparing change in number of days between 1971-2000 and 2071-2100 pAWSSI averages.*

The temporal variations of the end of the winter season again did not experience a significant change (Figure 3.2.4). The end date stays constant for the most part because of the criteria for winter with AWSSI. This does confirm that the average end of winter is not projected to increase.

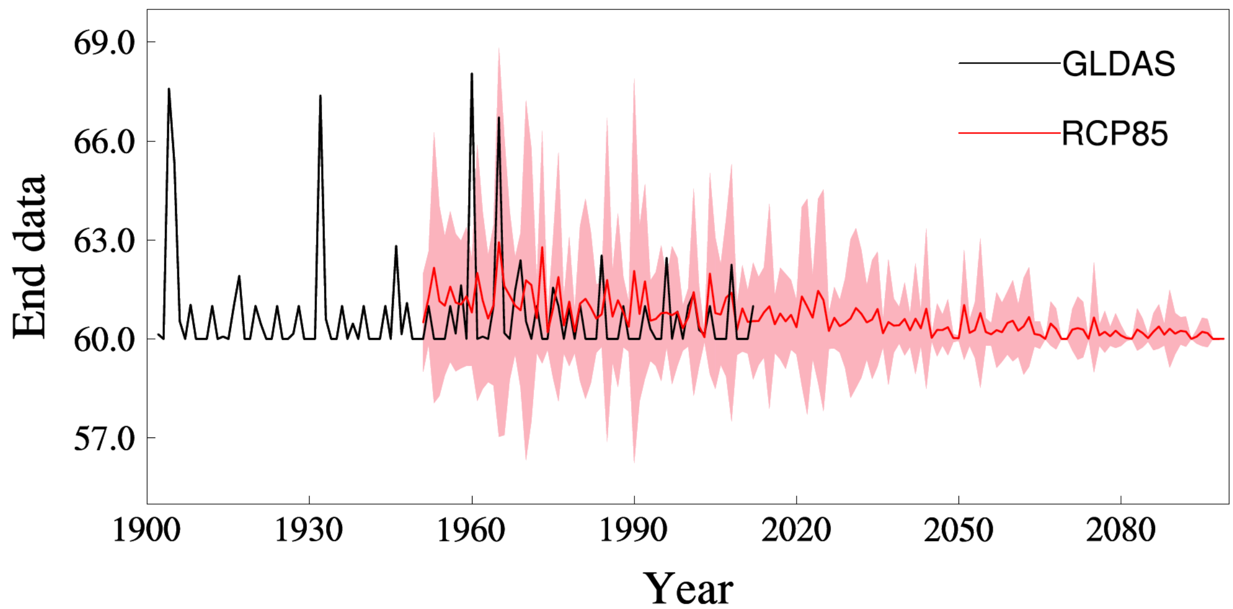


Figure 3.2.4 *Time series of the state-averaged pAWSSI scores for Arkansas. Black line is based on GLDAS during 1901-2012, while red line is based on the ensemble of the 20 CMIP5 models during 1950-2100. The pink shading denotes one standard deviation of the 20 CMIP5 model simulations.*

Length of the winter season is a good indicator of a winter's severity and is a combination of both the start and end of the winter season. On average the length of the winter season for the state of Arkansas ranges from about 91 to 94 days. Looking at the spatial distribution of the average length of winter for Arkansas under the RCP 8.5 scenario we can see a similar pattern as the observed years of 1971 to 2000 (Figure 3.2.5). With on average the longest winter's being in the northwestern parts of the state, but only varying 3 to 4 days from north to south.

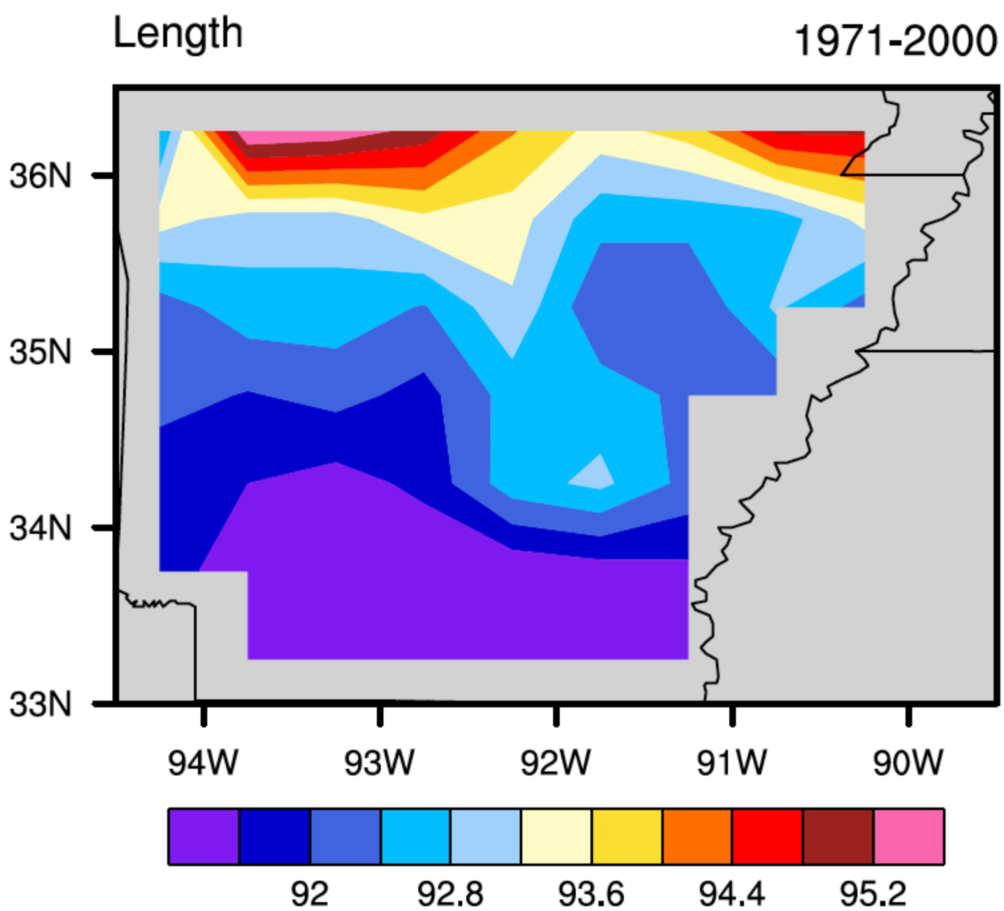


Figure 3.2.5 (a) *Spatial distribution of the average length of winter during (a) 1971-2000 and (b) 2071-2100 under the RCP8.5 scenario. (c) shows the projected changes in the length (days) during 2071-2100 relative to 1971-2000. The results shown are the ensembles of 20 CMIP5 models.*

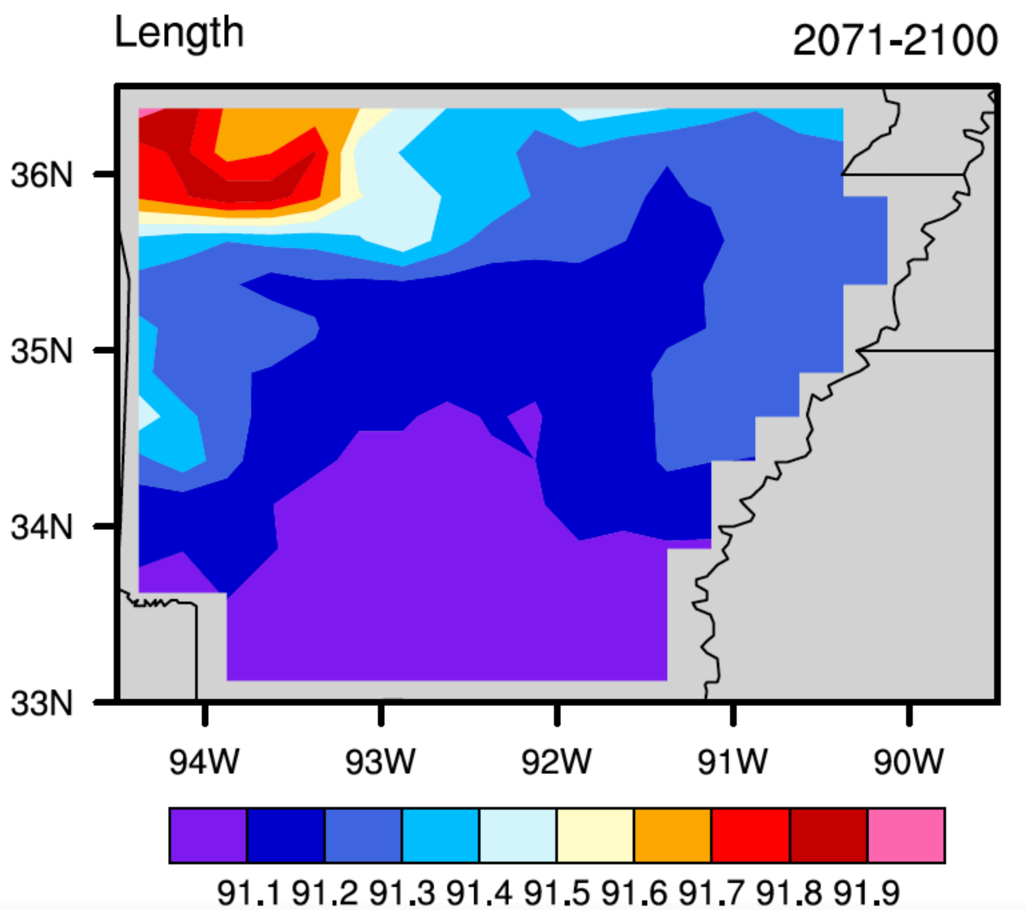

Length
2071-2100
36N
35N
34N
33N
94W
93W
92W
91W
90W
91.1 91.2 91.3 91.4 91.5 91.6 91.7 91.8 91.9

Figure 3.2.5 (b)

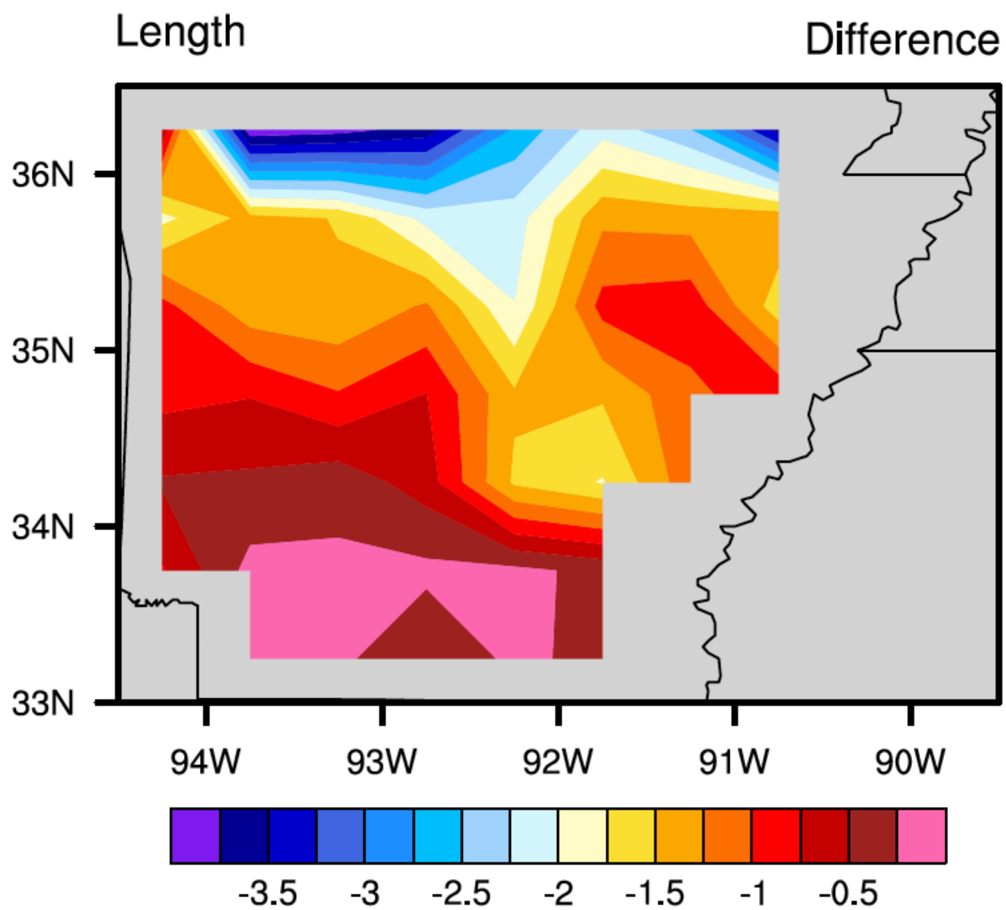


Figure 3.2.5 (c)

Looking at the RCP8.5 scenario, the length of the winter season on average does not experience any great chances throughout the years of 1971-2000 and the projected data from years 2071 to 2100 as shown in figures 3.2.5a and 3.2.5b respectively. The differences can be seen in figure 3.2.5c where the largest change was experienced in the northern third of the state where we see a decrease in average length of winter drop by one to two days, and up to 4 days in extreme northern Arkansas. This is expected as the start and end of the winter season also saw little change.

Looking at the timeseries in figure 3.2.6, we can see that the average length of the winter season has not experienced a significant change in the observed years of 1901 to 2012. The model data from years 1950 to 2010 also show little variability. This can be linked to the fact that the minimum winter season length for the AWSSI criteria is 92 days from December 1st to March 1st. The standard deviation from about years 2012 to 2030 could suggest a couple years of higher variability from year to year and a few outlier years. The standard deviation after about 2030 becomes less variable and this is because the average length of winter is expected to be about 92 days which is the minimum.

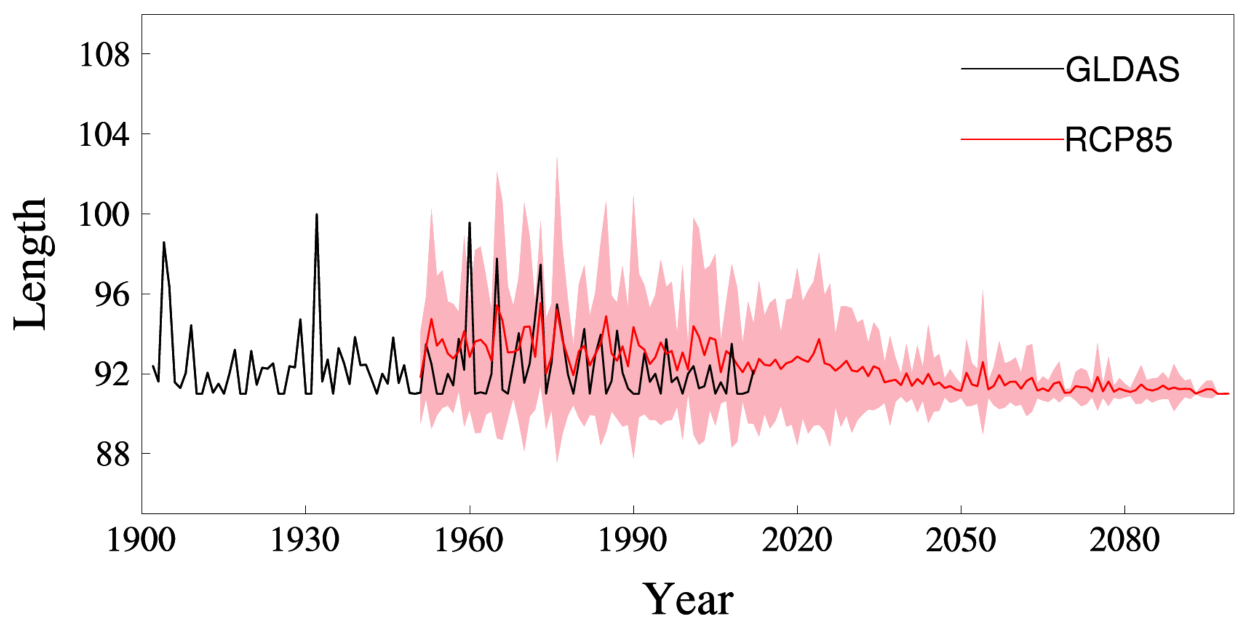


Figure 3.2.6 *Time series of the state-averaged pAWSSI scores for Arkansas. Black line is based on GLDAS during 1901-2012, while red line is based on the ensemble of the 20 CMIP5 models during 1950-2100. The pink shading denotes one standard deviation of the 20 CMIP5 model simulations.*

3.5 AWSSI (Temperature) and (Snow)

The temperature based pAWSSI (AWSSI-temp) depicts the impact of winter temperature variability on the winter severity. This variable is calculated by taking away the snow parameter from AWSSI and calculating AWSSI by using only temperature. This projection could give us an idea of average winter temperature trends for about the next century. The spatial distribution under RCP 8.5 scenario confirms that on average from 2071 to 2100 (Figure 3.3.1b) the temperature dependent AWSSI will be much lower resulting in milder winter seasons compared to the present-day conditions (Figure 3.3.1a). For example, on average the northwestern part of the state experiences the higher AWSSI totals and more severe winter. In the averages from the observed data from 1971 to 2000 we see values of over 120 for that part of the state. Compare that to an average from 45 to 50 in the averages from 2071 to 2100. This is very telling of a noticeable decrease in winter severity that is projected under RCP 8.5. In figure 3.3.1c we can see 60%-76% decrease in AWSSI-temp throughout the state. Areas in the southern Arkansas have the largest percent change over 70%. Under this scenario there would be very mild winters, not only in the southern part of the state but also other areas like Northwest Arkansas with average AWSSI temperature scores cut by more than half.

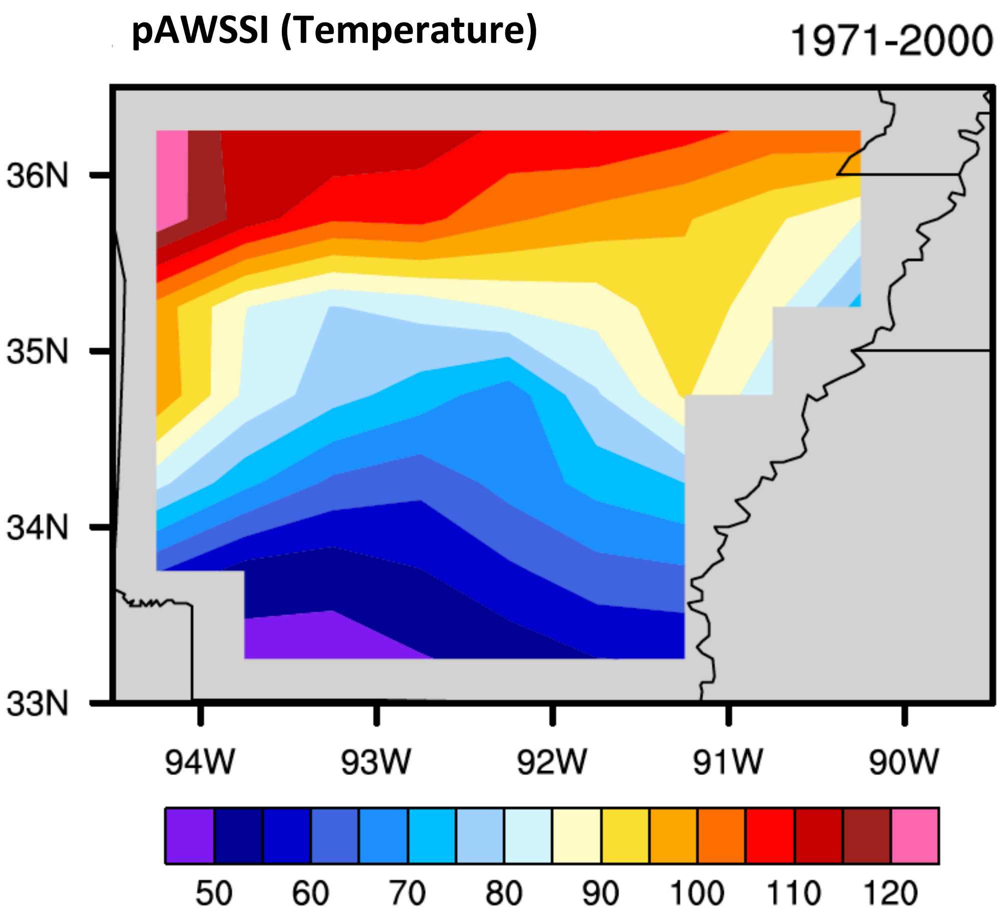
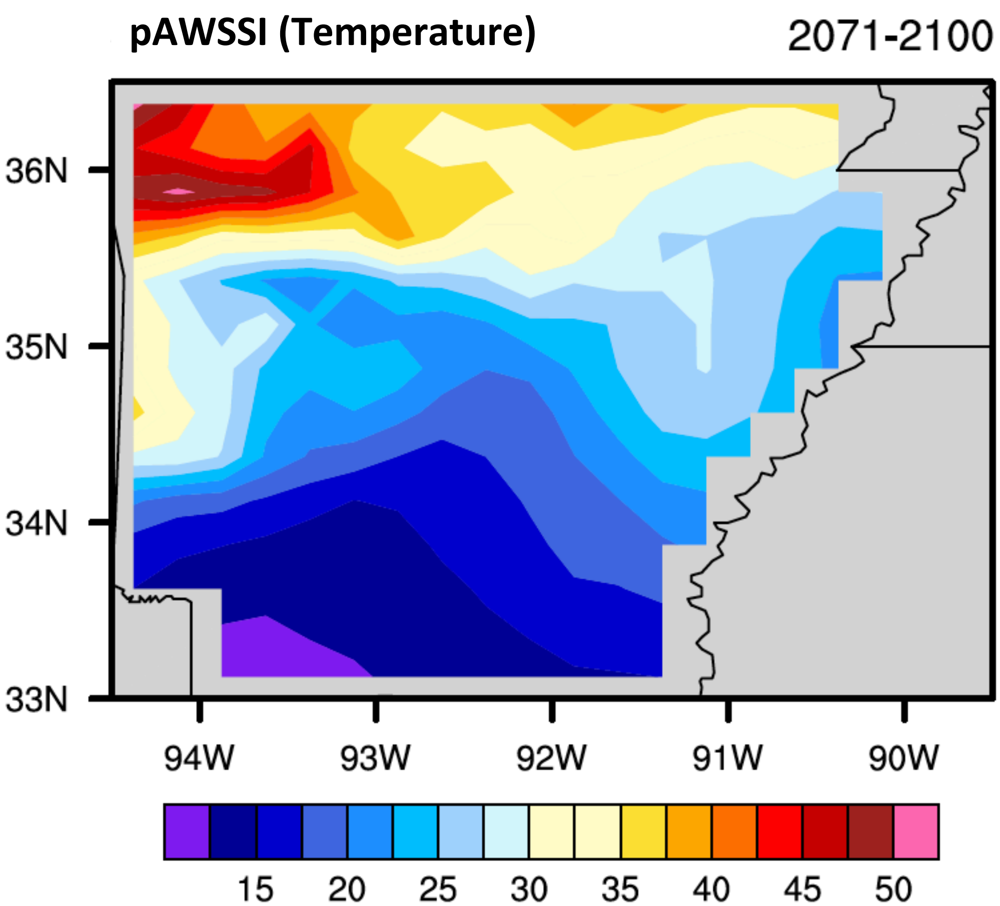


Figure 3.3.1 (a) Spatial distribution of the average pAWSSI using the temperature variable of winter during (a) 1971-2000 and (b) 2071-2100 under the RCP8.5 scenario. (c) shows the projected changes in AWSSI temperature (days) during 2071-2100 relative to 1971-2000. The results shown are the ensembles of 20 CMIP5 models.



pAWSSI (Temperature)
2071-2100
36N
35N
34N
33N
94W
93W
92W
91W
90W
15
20
25
30
35
40
45
50

Figure 3.3.1 (b)

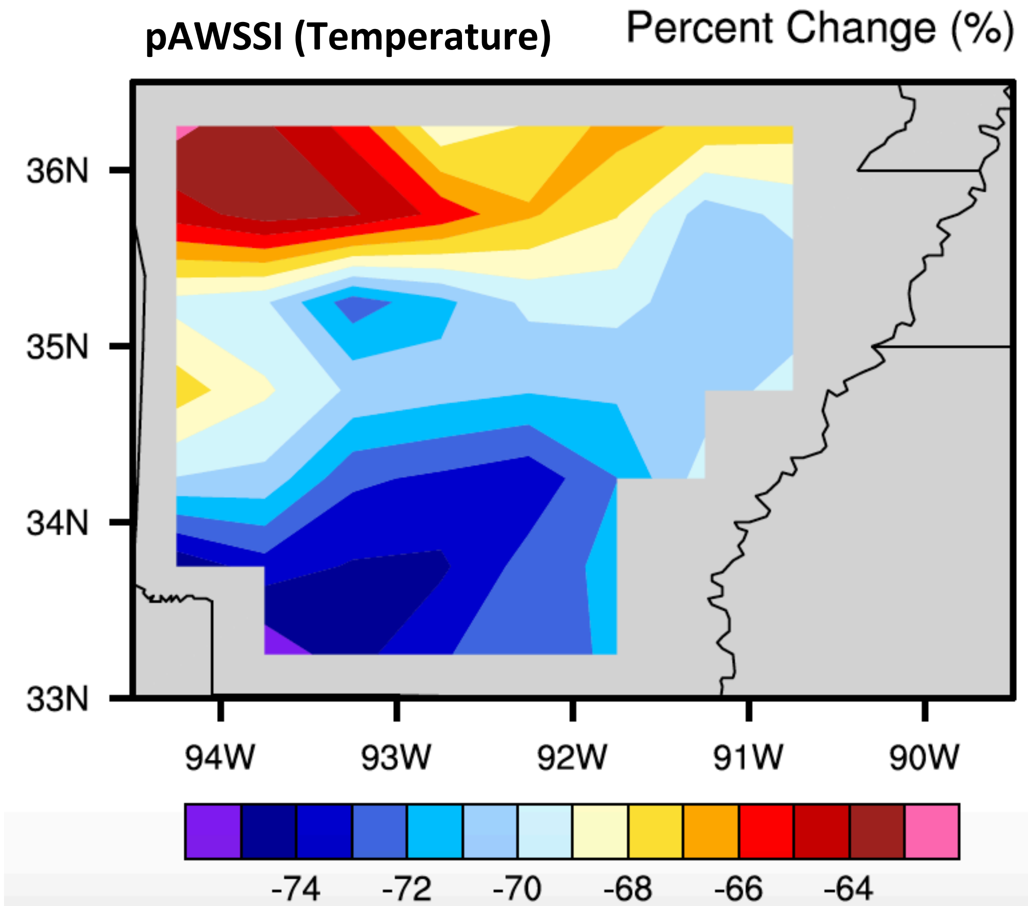


Figure 3.3.1 (c)

Figure 3.3.2 shows the temporal variations of the state-averaged AWSSI-temperature from 1950-2100. There is a prominent trend down starting at about 1990, meaning a decrease in winter severity based on temperature, and in this case also a trend towards warmer winter season on average for Arkansas. Under the RCP 85 scenario the average Arkansas winter severity using only temperature continues to show a sharp decrease through 2100.

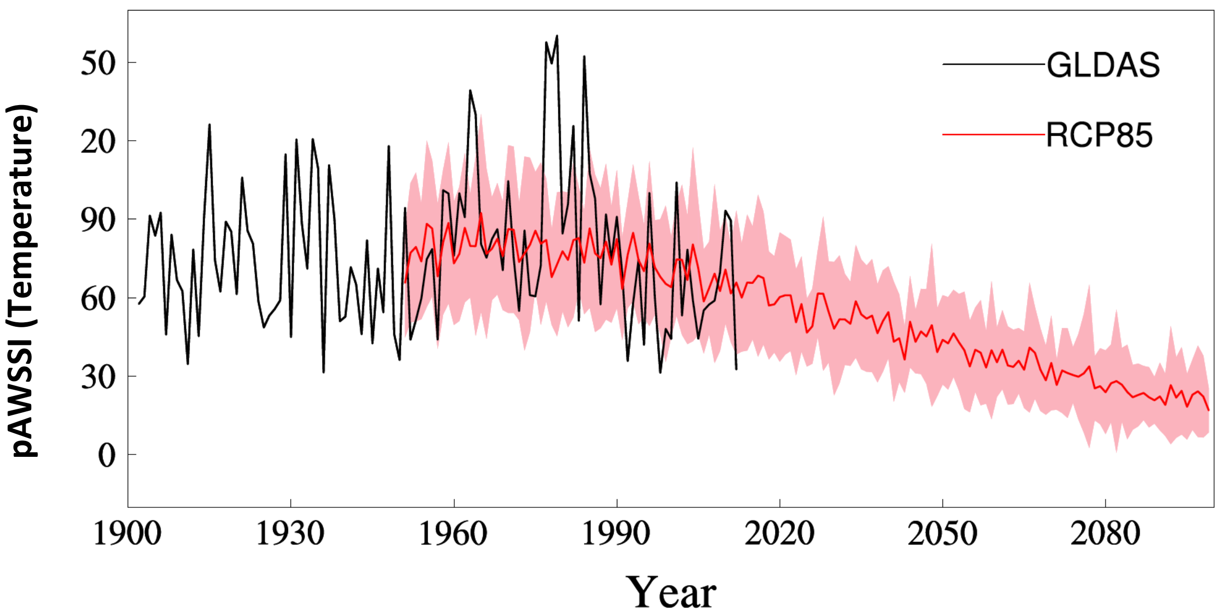


Figure 3.3.2 *Time series of the state-averaged pAWSSI scores for Arkansas. Black line is based on GLDAS during 1901-2012, while red line is based on the ensemble of the 20 CMIP5 models during 1950-2100. The pink shading denotes one standard deviation of the 20 CMIP5 model simulations.*

Much like the temperature based AWSSI, the snow based AWSSI using only snowfall and snow depth to calculate AWSSI. The spatial distribution of the projected average snow based AWSSI scores trend to be the highest in the northwestern and northeastern sections of the state in the 1971-2000 (Figure 3.3.3a). Compared to the 2071-2100 averages (Figure 3.3.3b), we can see a noticeable decrease with the highest values only in the 7-8 range compared to 16-24 from 1971-2000. This can be visualized in Figure 3.3.3c with the percentage change between the two time-frames. It can be concluded that the western and northeastern Arkansas would experience a sharp decrease in snowfall through 2100 under the RCP 85 scenario. It also indicates that Arkansas will barely receive any meaningful snowfall by the end of this century.

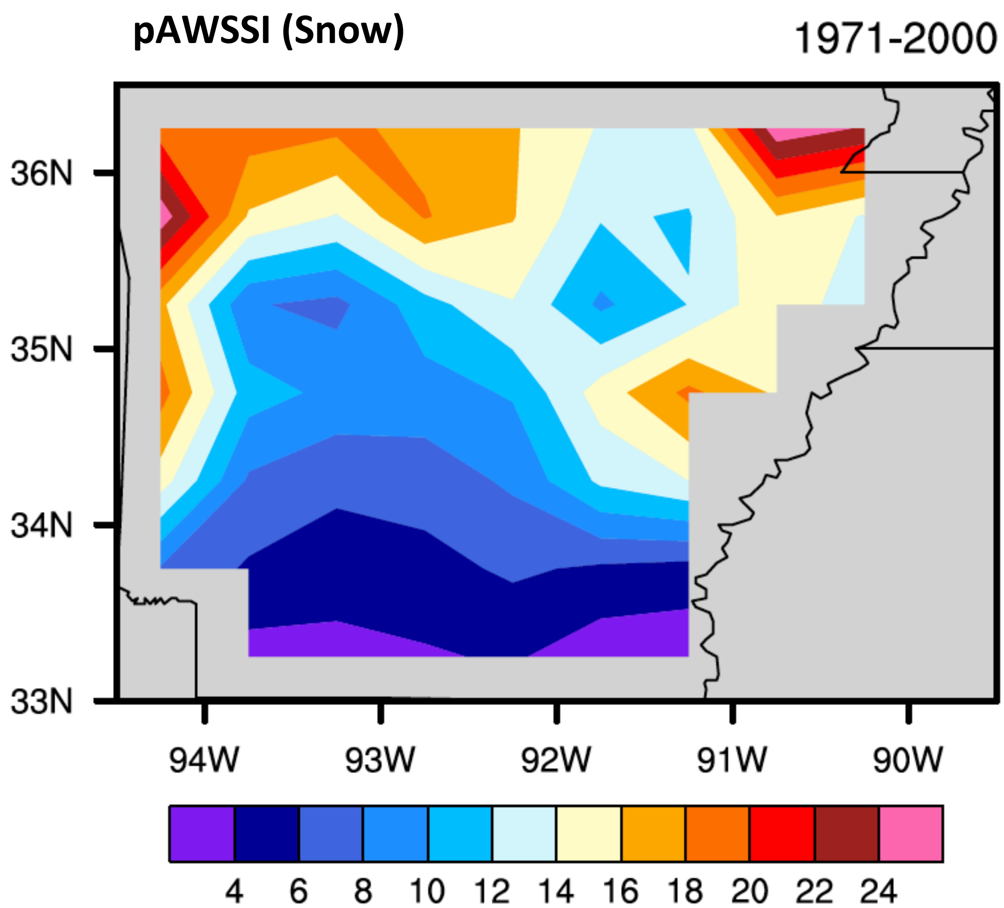


Figure 3.3.3 (a) Spatial distribution of the average AWSSI using the snow variable of winter during (a) 1971-2000 and (b) 2071-2100 under the RCP8.5 scenario. (c) shows the projected changes in AWSSI snow (days) during 2071-2100 relative to 1971-2000. The results shown are the ensembles of 20 CMIP5 models.

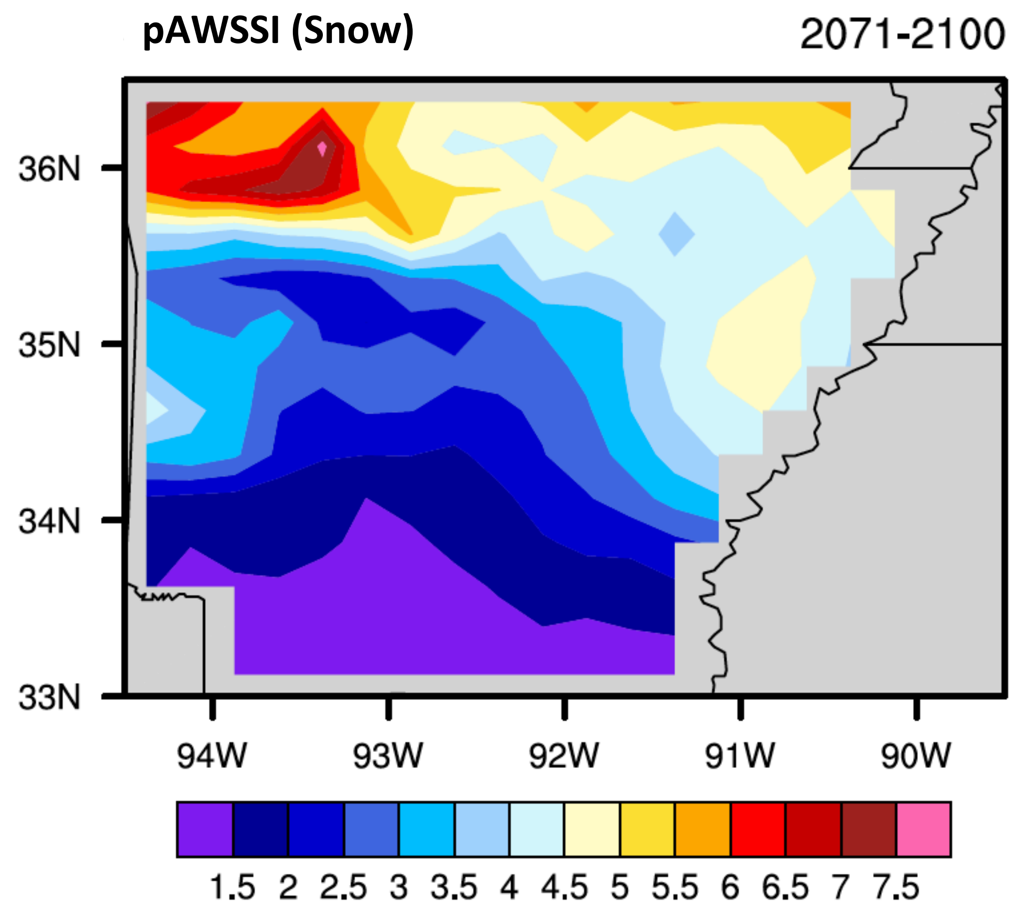

pAWSSI (Snow)
2071-2100
36N
35N
34N
33N
94W
93W
92W
91W
90W
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
7.5

Figure 3.3.3 (b)

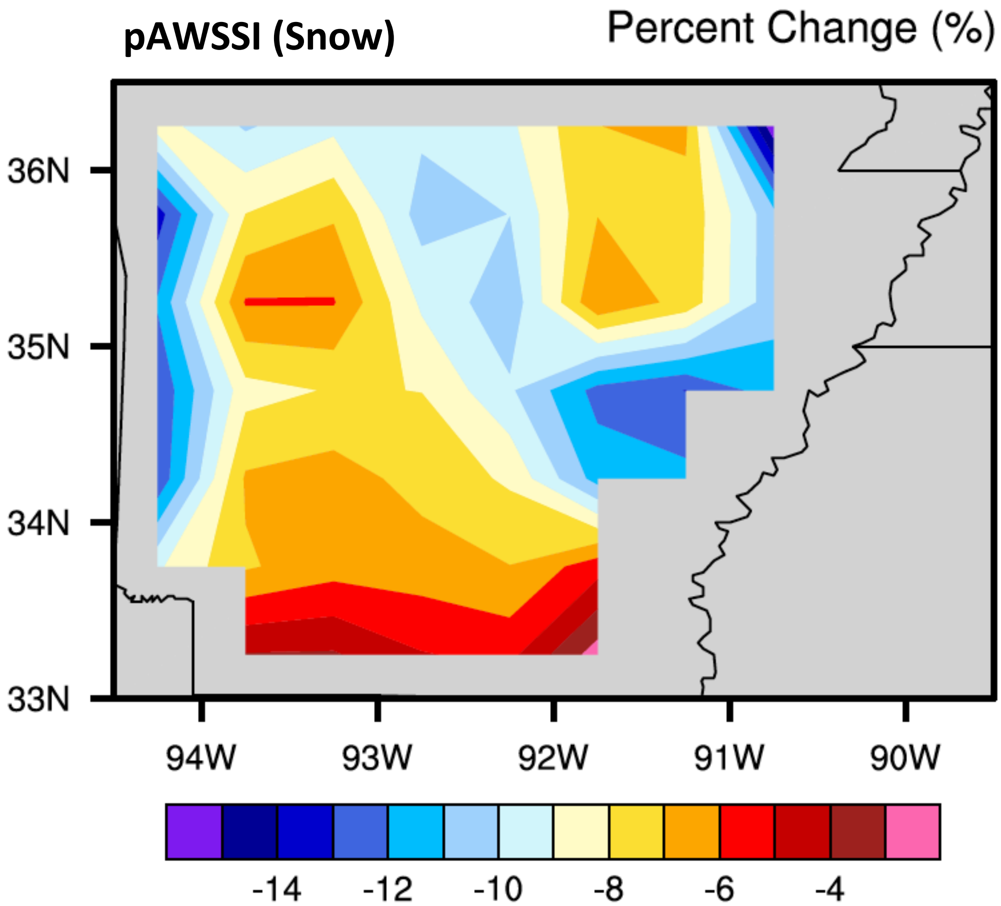


Figure 3.3.3 (c)

Figure 3.3.4 illustrates the temporal variations of snow dependent AWSSI for the years of 1950 to 2100 based on the 20 CMIP5 models. The models suggest similar trend during 1950-2012 as the GLADS, albeit the models overestimate the snowfall. This is understandable because the models have large bias in simulating the precipitation comparing to temperature. Arkansas on average already sees very little in snowfall so this is not a great variable for this part of the country. The snow dependent AWSSI under the RCP8.5 scenario also is projected to have little change throughout the 21st century. Snowfall is mostly concentrated to the northern sections of the state but as a statewide average the snow dependent AWSSI is fairly low to begin with so there is little room for change. Overall, on average the AWSSI snow dependent variable will continue to decrease slightly and the mostly affecting areas of northern Arkansas where snowfall is more prevalent.

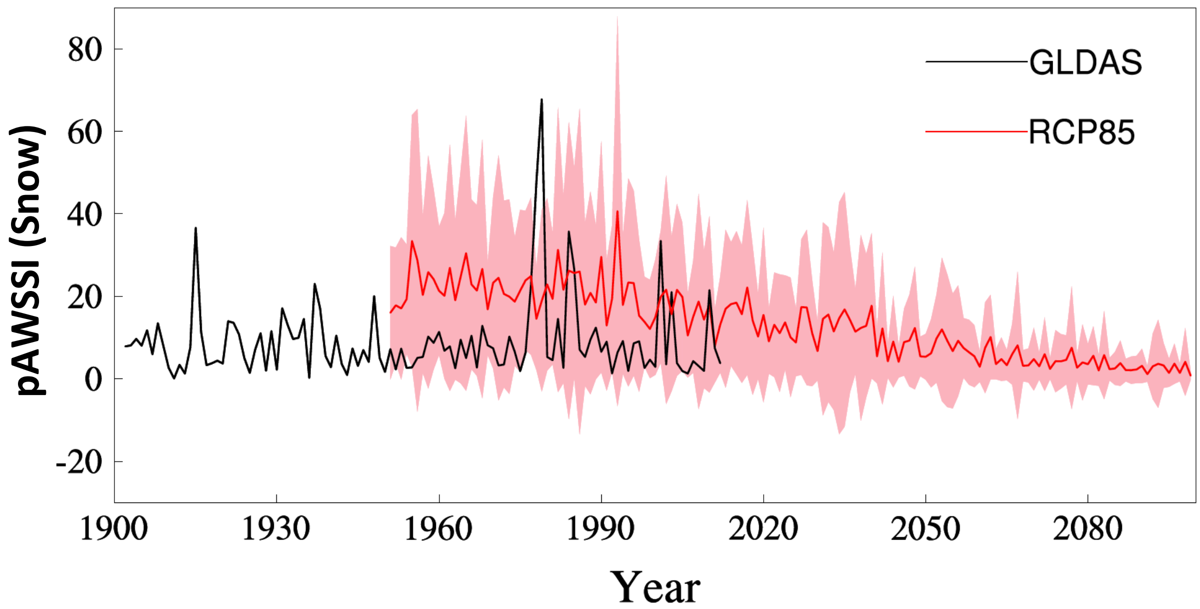


Figure 3.3.4 *Time series of the state-averaged pAWSSI scores for Arkansas. Black line is based on GLDAS during 1901-2012, while red line is based on the ensemble of the 20 CMIP5 models during 1950-2100. The pink shading denotes one standard deviation of the 20 CMIP5 model simulations.*

3.6 Conclusions

In this chapter the pAWSSI and related variables were examined, and how they are projected to change in the future under the RCP 8.5 scenario. I also compared the differences between the present-day averages from years 1971-2000 and the end of this century from 2071-2100. This study focused on how the differences vary spatially and what areas of the state are more affected by the projected climate changes. The temporal variations of the winter severity were examined based on the state-averaged pAWSSI and related indices during 1950-2100. The modeled winter severity was also compared to the observation based GLDAS data during the overlapping years (1950-2012). It was concluded that the AWSSI as well as all its parameters (start date, end date, length of winter) are all projected to decrease slowly and lead to less severe winters through the end of the century. This can also be said about the snow dependent variable of AWSSI (snow) and its counterpart AWSSI (temperature). The state-wide average AWSSI (temperature) variable is expected to have very significant decrease through 2100 with over a 60% drop throughout the state, leading to very mild winter seasons. This indicate that, under the RCP 8.5 scenario, we will experience a significant change in what an average winter season looks like for Arkansas.

Chapter 4: Conclusions

This study evaluated the winter severity in Arkansas using a newly developed AWSSI based on observations and multiple model simulations during 1901-2100. More harsher winters usually appear in the northern and northwestern sections of the state. The state averaged AWSSI show notable year to year variations and a downward trend during the instrumental period, especially during the recent decades, suggesting less harsh winter in the state. This changes in AWSSI are closely linked to the winter temperature. Temporal variations of pAWSSI are also influenced by large-scale atmospheric and oceanic indices, such as the NAO and PDO.

For the future projection, the modeled daily temperature and precipitation under the RCP8.5 scenario from 20 CMIP5 models were analyzed. The downward trend in AWSSI during the instrumental period is projected to continue and accelerated in the future under the RCP8.5 scenario. The AWSSI as well as all its parameters (start date, end date, length of winter) are all projected to decrease and lead to less severe winters through the end of the century. Under the RCP 8.5 scenario, we will experience a significant change in what an average winter season looks like for Arkansas. These trends towards a decrease in winter severity can be associated with the overall warming and change in much of the Earth's climate due to anthropogenic forcing.

The effects of a milder winter might not be greatly significant for Arkansas but could be detrimental for states such as California and Colorado that rely on snowpack for drinking water and agriculture. This study only focused on Arkansas, so we do not know what the overall implications would be on the rest of the country or the world.

Future Work

There are multiple ways to further expand this thesis work. Analyzing the winter severity trends and projected changes for the entire country or even different parts of the world would be something that could add valuable information to this study. Being able to understand the greater picture of winter severity and verify what areas have the most rapid decrease in winter severity, as well as looking for areas that might be seeing an increase in winter severity. Additionally, this study only evaluated the future winter severity under the RCP8.5 scenario. Further study should expand to include multiple scenarios. For example, the intermediate scenario (RCP4.5) and the very stringent scenario (RCP2.6). The magnitude of the future winter severity may be different under these lower greenhouse gases emission scenarios. It is also necessary to evaluate the changes in winter severity based on the CMIP6 models under multiple shared socioeconomic pathways (Eyring et al., 2016) and compare to the simulations based on CMIP5 models.

Another way to expand on this research would be to study how winter severity affects people's overall quality of life and day to day lives. Working with social scientists to better understand how a decrease or increase in winter severity might affect the day to day lives of average American's or around the world. Depending on how severe a winter is might decide if someone buys a certain type of vehicle or other supplies. Winter severity can also have a major effect on energy consumption such as natural gas for heating purposes. Examining heating bills and consumption and how it correlates with winter severity would be an interesting study. Along with projecting how energy consumption will change throughout the years with the project winter severity trends.

As mentioned before using the winter severity index to assist with economic modeling could become very helpful. Winter severity may influence the overall global economy and knowing how to plan and mitigate for future changes will become increasingly crucial.

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