MICHIGAN DOT CLIMATE VULNERABILITY ASSESSMENT

Climate Data, Models, and Analysis

Task 4 Technical Report

prepared for

Michigan Department of Transportation

prepared by

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with

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1.0 INTRODUCTION

Cambridge Systematics is leading a climate vulnerability assessment for the Michigan Department of Transportation (MDOT),with a focus on how climate and extreme weather risks can be integrated into the DOT's planning practices. This work includes identifying the primary climate stressors impacting the transportation system, examining risks from future climate and extreme weather impacts, assessing the vulnerability of transportation assets to those risks, and defining strategies for incorporating this information into asset management.

The purpose of this technical report in supporting the project is threefold:

1. Document the climate stressors identified for analysis during this study;
2. Describe the process for selecting climate models and weather data to develop spatially disaggregated climate projections for the entire State, organized by climate region; and
3. Introduce preliminary findings from the climate analysis that will inform risk management decisions within the State's asset management and planning programs.

Several critical steps have been taken in preparation for completing this task. A thorough data collection effort involving detailed MDOT transportation asset data and weather station data for the State of Michigan was assembled (more on weather station data can be found in Section 2.0 of this report). Data gaps critical to the analysis were identified and efforts were undertaken to obtain supplemental date where available. Concurrent with these data collection and preliminary analysis steps, two meetings of a Technical Advisory Committee (TAC) assembled to guide this study effort were held to first, present the study scope and objectives, and second, to respond to the study team's methodology and process to date for developing the climate modeling, and criticality and vulnerability assessment approaches. Through discussion with the TAC and an internal working group, the key issues and climate stressors of greatest concern were identified on which to focus the climate modeling and vulnerability assessment steps. These conversations and the processes for refining the study scope are further described in Section 2.0.

2.0 DEFINING CLIMATE VARIABLES

In order to define the climate variables to be examined in the analysis, it is important to first identify what is known (and unknown) about changes to Michigan's climate.

Global greenhouse gas concentrations are rising. Concentrations of greenhouse gases, such as carbon dioxide (CO_2), have increased and are highly likely to continue increasing over many decades because of the increasing use of fossil fuels and other human activities. These gases trap radiation in the atmosphere; increased radiation results in higher temperatures.

We know that the increase in greenhouse gas concentrations has strongly contributed to rising global temperatures. Based on information of past climates (paleoclimatology), and from climate models that the main reason the average temperature of the Earth's atmosphere has increased is because of higher greenhouse gas concentrations.

It is also know that temperatures will continue to rise – but it is unclear by how much. Greenhouse gas concentrations are continuing to rise and this will result in additional warming of the atmosphere. The amount of future warming depends not only on the amount of greenhouse gases released; it also depends on how the Earth's climate system responds to the buildup of gases. For example, there is a 90 percent chance that a doubling of $CO_{2\,(}$which will likely happen this century) will increase average global temperature on Earth between 2°F and 11°F (1 to 6°F), with some places warming more than others. Virtually all of the Earth's land areas, including all of Michigan, are projected to get hotter.

With higher temperatures, other changes in the climate are certain to happen. Average precipitation across the world will increase, but not all areas will get wetter. In general, Michigan is expected to get wetter overall. Indeed, total precipitation over the State has increased in recent years. Although the vast majority of climate models project an increase in precipitation over Michigan, a few climate models estimate a reduction. In addition, many models project an increase in winter precipitation and a decrease in summer precipitation. There already has been an increase in precipitation intensity and it is likely that even more intense precipitation in the future.

Natural variability will still affect future climate. Even though there is a long-term global warming trend, natural variability still affects year-to-year and decade-to-decade climate. These forces include volcanic eruptions, changes in solar radiation, and shifts in ocean circulation. Natural variability of the climate means that one year may be colder or drier than the one before. But, scientists are confident that over a number of decades the planet will experience a strong warming trend. Indeed, looking further into the future – for example, 50 to 100 years – the more likely it is to see clear and significant warming.

The study team will examine the key issues and climate stressors of primary concern for MDOT transportation asset managers.

2.1 Key Issues of Concern

MDOT transportation staff and the TAC identified several key issues of concern to both immediate and long-term asset management operations and maintenance programs. More frequent and intense precipitation events have occurred in recent years, leading to increased erosion, bridge scour, and localized flooding issues. Specific interest in future frequency of extreme precipitation events with a short duration (i.e., 3" to 6" in a 24-hour period) was identified as a key issue for analysis. In addition to extreme precipitation events, seasonal change in precipitation also is a concern. Precipitation increases in winter months, combined with decreases in summer months, create optimal conditions for increased wildfire risk.

Increased winter temperatures and greater temperature variability also are a concern. Warmer winters could result in decreased snowfall and increased rain, which pose different operations and maintenance challenges for safe, passable roadways. Furthermore, increased temperature variability in the winter months leads to greater freeze/thaw cycles, damaging the integrity of the roadway.

The anticipated annual and seasonal shifts in both temperature and precipitation may have significant impacts on the Great Lakes. Warming temperatures could result in reduced ice cover and more open water, which may lead to more lake effect storms. Drier conditions, resulting in low water levels, may result in significant economic impacts to both recreation and freight. Given the wide variety of factors that influence lake levels and the broader microclimate they inspire, climate models are unfortunately rather poor at projecting impacts to the Great Lakes under different climate scenarios. However, a tremendous amount of research has been done on Great Lakes water levels, which this assessment will draw upon through a literature review.

2.1.1 Climate Stressors for Analysis

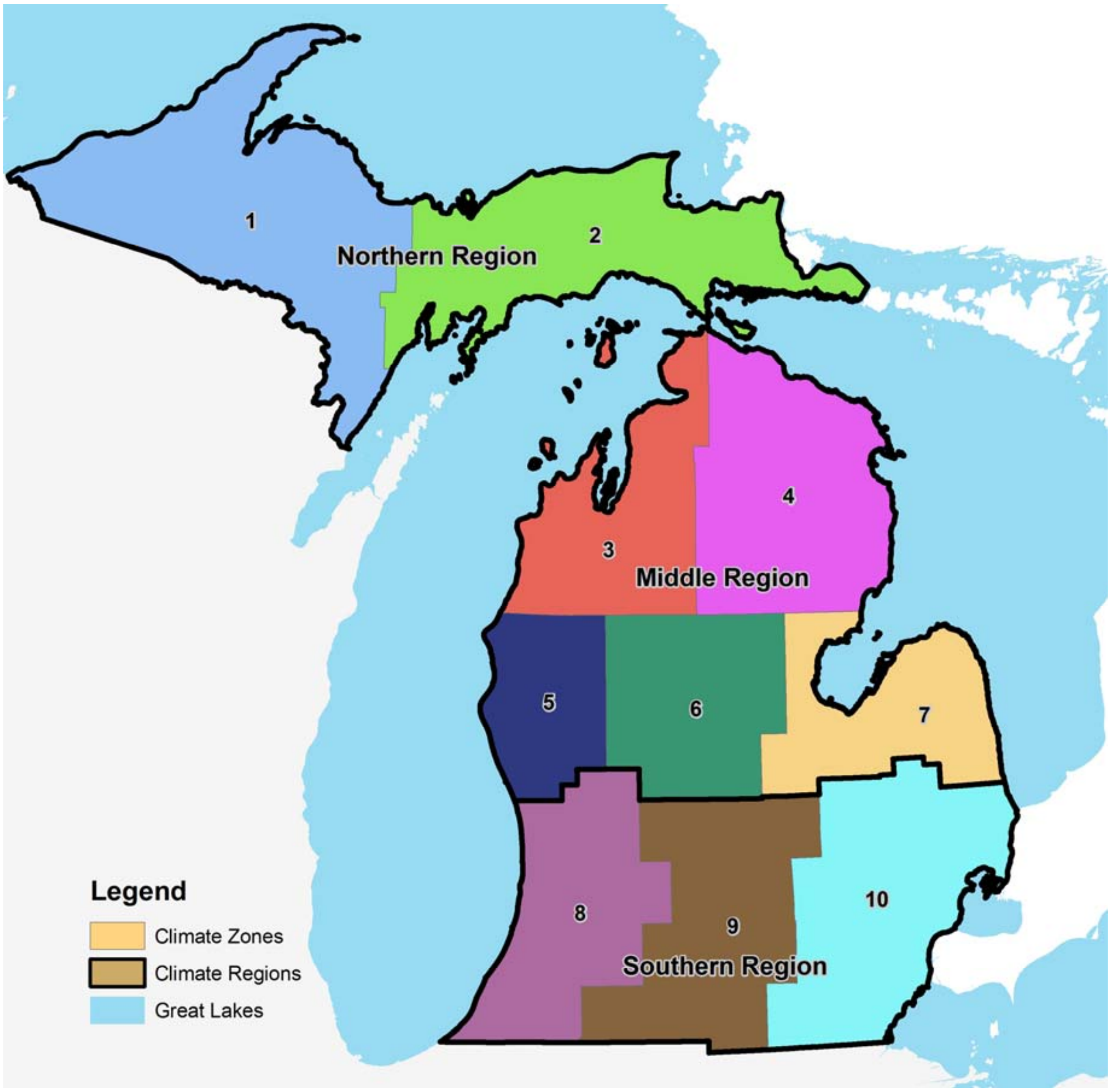
The key issues of concern identified by MDOT are represented in the following table. The primary climate stressor for each issue, or issues, has been operationalized for analysis by the study team.

Table 2.1 Climate Variables to Examine

Issue(s) of Concern	Climate Variable for Analysis	Operationalized Climate Variables
Increased erosion from intense precipitation, decreased snow/increased rain (specific interest in extreme precipitation events in a short-time period (three to six hours), bridge scour	Extreme precipitation	• Change in 24-hour rain event (30-year, 50-year, 100-year events) • Change in precipitation as snow versus rain
Freeze/thaw Great Lakes ice cover (and impact on lake effect snow)	Winter temperatures/ temperature variability	• Number of days below freezing (change from present for 2050, 2100) • Number of consecutive frost-free days (change from present for 2050, 2100)
Road buckling	Extreme summer temperatures	• Number of days over 95 degrees
Lake levels		• Qualitative analysis based on research
Wildfire		• Qualitative analysis based on research

The results of the climate analysis were generated for 10 climate regions in Michigan, defined by the Great Lakes Integrated Science and Assessment (GLISA) at the University of Michigan. For this report, most analyses are summarized by three broader regions (Figure 2.1): the Northern region encompasses the Upper Peninsula, the Middle region encompasses the northern portion of the Lower Peninsula, and the Southern region encompasses the southern portion of the Lower Peninsula and the State's two largest urbanized areas. This will allow for a more focused and manageable approach to understanding the range of possible climate futures across the State, and the potential impacts to MDOT transportation assets.

Figure 2.1 Michigan Climate Regions and Groupings



3.0 APPROACH TO CLIMATE ANALYSIS

To project the change in future climate, a quality baseline data set was developed for historical climate conditions and combined with changes projected from the climate model outputs. This analysis examines both changes in average climate (e.g., annual, seasonal, and monthly), and changes in extreme events. Raster surfaces of monthly average climate conditions are available from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) (PRISM Climate Group, 2011).[1] Monthly mean grids at approximately 800-meter resolution are available for each climate variable (maximum and minimum temperature, and precipitation) by individual month from 1981 to 2010. While other raster baseline data exist, such as the Climatic Research Unit East Anglia University dataset at 0.5 degree (~60 km), this approach utilized the PRISM dataset as it represents the highest resolution climatic dataset available, thus capturing regional and local weather patterns (Daly et al., 2008). Baseline climate variables are based on average climate conditions representing the 1981 to 2010 time period. This time period was chosen over the more standard 1951 to 1980 time period in order to capture the current conditions and climate trends. Using this baseline, this report examines the change in average conditions, including annual and seasonal-time steps.

For extreme event analysis, daily observed data from climate stations was utilized to study the changes in frequency and intensity of extreme events. Daily station data is available from National Oceanic and Atmospheric Administration’s National Climatic Data Center (NCDC). However, unlike the average climate data, station data is site-specific and less uniform. Therefore, the data was screened based on the period of record and quality of the data (e.g., number of records without missing days) prior to using it in the analysis.

Recognizing the need to have a consistent period of record for each site, after correspondence with the Great Lakes Integrated Sciences and Assessments (GLISA) group and examination of the spatial distribution of stations across the study area, two sets of station data were developed for the analysis. The primary data set was constrained to those stations with a consistent 50-year period of record (1961 to 2010), 95 percent temporal coverage (i.e., 95 percent of the days within the reporting period have data), and at least 25 years of data for any 30-year block. In order to generate a spatially continuous surface across the study area, additional climate stations were required to ensure that any location estimated was within 30 miles of a climate station (following a recommendation made by GLISA). This “secondary” data set was constrained to those stations with a 30-year period of record extending to at least 2008 and with at least 80 percent temporal coverage (i.e., 80 percent of the days within the reporting period have data). Lastly, a spatial

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[1] A raster surface is a continuous field of values that varies over space. The surface is a grid of equally sized cells that contain the attribute values for expected climate variables.

filter was developed to identify areas where the nearest station is beyond 30 miles (low confidence areas).

3.1 Future-Time Periods

While climate models can simulate day-to-day climate over a large number of years, the data generated by these models are extremely large and difficult to manage. More importantly, there is little confidence in the models' simulation of year-to-year and decade-to-decade changes, because the climate of any given year might vary significantly from an overall pattern or trend. There is more confidence in model simulations of average climate over a 20-year period. For this analysis, climate change scenarios were developed for two future-time periods: 2050 and 2100. These dates represent average climate conditions over a 20-year period centered on the respective year (e.g., 2050 represents average conditions from 2041 to 2060). As such, the results in this report compare a a simulation of the current climate over a 20-year period (e.g., 1986 to 2005) with a simulation of a future 20-year period (i.e., 2041 to 2060 for 2050 and 2091 to 2110 for 2100).

3.2 Emission Scenarios and Climate Sensitivity

The Intergovernmental Panel on Climate Change (IPCC) has developed two sets of emission scenarios based on change in GHG and sulfate aerosol emissions for use in global climate modeling. The IPCC's 4th Assessment used the Special Report on Emission Scenarios (SRES; Nakićenovic et al., 2000), which grouped emissions into categories (B1, B2, A1B, A2, and A1FI) based on different assumptions of demographic, social, economic, technological, and environmental changes. However, in the IPCC's 5th Assessment, which was just released, the panel instead used the concept of Representative Concentration Pathways (RCP). The four RCPs correspond with different radiative forcings (i.e., how much additional energy is trapped in the atmosphere by increased greenhouse gas concentrations), measured in watts per square meter in 2100 (IPCC, 2014; Moss et al., 2010). The RCPs represent a broad range of potential climate outcomes, and were developed based on an extensive literature review. The four RCPs used in the IPCC's 5th assessment are:

- **RCP 2.6**. This pathway represents the scenarios in the literature review that lead to very low greenhouse gas emissions relative to other scenarios. In this scenario, greenhouse gas emissions are reduced significantly over the remainder of the century, resulting in a midcentury "peak" in radiative forcing followed by a slight decline.

- **RCP 4.5**. This concentration pathway represents a stabilization scenario where total radiative forcing is stabilized before 2100 through a series of technologies and strategies for reducing greenhouse gas emissions.

- **RCP 6**. Similar to RCP 4.5, this concentration pathway represents a stabilization of radiative forcing. In RCP 6, radiative forcing is stabilized after 2100 rather than before.

- **RCP 8.5**. This concentration pathway represents increasing greenhouse gas emissions as the century progresses, leading to high-greenhouse gas concentrations by 2100 (IIASA, 2009).

The project team utilized the projections from the latest IPCC report because it is expected that these scenarios will be widely applied. Additionally, while there is no consensus on which RCP is most likely to happen, the team suggested using RCP6 (hereafter "medium" emissions scenario) and RCP8.5 (hereafter "high" emissions scenario), because they are most consistent with recent global trends in greenhouse gas emissions. The team also recognized that while RCP 4.5 is widely used in other analyses, it would take extraordinary global policy measures to achieve and is therefore not likely. The medium and high scenarios were chosen because these levels of emissions appear likely without significant changes in behavior, and risk analysis is more useful when the scenarios reflect actual risk.

The estimated sensitivity of radiative forcing is usually expressed as the amount that global average temperature is projected to increase due to a doubling of CO_2 in the atmosphere. The IPCC's 4th Assessment reported the likely range in climate sensitivity between 2 and 4.5°C (3.6° and 8.1°F), with 3°C(5.4°F) considered the most likely value (IPCC, 2007). The 5th Assessment did not give a most-likely climate sensitivity, but concludes that climate sensitivity is likely between 1.5 and 4.5°C and very likely between 1 and 6°C (1.8 and 10.8°F). After discussion with MDOT, and based on the fact that each climate model has its own climate sensitivity, a median value from the range of climate models was used as the most likely climate sensitivity for this analysis.

3.3 Global Climate Models

Global Climate Models are used to project changes in global climate. These models capture the interaction among the atmosphere, oceans, land surface, and ice over the entire Earth to project climate variables including temperature, precipitation, and winds for each cell. Climate models are developed by universities and governmental research laboratories across the globe but are coordinated through the Coupled Model Intercomparison Project (CMIP) to provide some standardization of protocols. The IPCC's 4th Assessment included 24 climate models, known as CMIP3, which were run under the corresponding set of SRES emission scenarios. The IPCC 5th Assessment includes over 40 models from over 20 modeling centers in North America, Europe, and Asia and run under the set of corresponding RCPs. As above, the output from the IPCC's latest report corresponding to the CMIP5 set of models was used.

The combination of climate model, radiative forcing, and climate sensitivity results in a high degree of variability, especially at the season or monthly-time step. While it is possible to provide results from the full combination of these "scenarios," the large number of results would be overwhelming.

For example, output from 40 climate models and 2 RCPs would produce 960 monthly projections for each climate variable considered. In light of this, the project team used a subset of scenarios that capture a wide range of variability while also providing a central projection. The scenarios were selected by first generating summaries of average annual change in temperature and precipitation by the 10 NOAA Climate Divisions within the State[2] for the subset of 21 climate models available that can provide estimates of extreme precipitation.[3] The study team then generated scatter plots of the temperature and precipitation changes and selected the 5 "bounding" models from each region that represent a diversity of projections. The criteria for selection were based on the 99th, 50th, and 1st percentiles of temperature and precipitation combinations to capture the Hot/Dry, Hot/Wet, Middle, Cool/Dry, and Cool/Wet models.

Figure 3.1 shows a scatter plot of change in average annual maximum temperature (°C) and precipitation (percent) by climate for climate division 1 under the high-emissions scenario in 2100. Each dot represents a climate model projections. The square dots are the subset of models that can produce estimates of extreme weather events (a critical factor for this study). The red square dots are the five climate models selected for this study. They were selected using the 99th, 50th, and 1st percentile of temperature/precipitation values from the full set of models.

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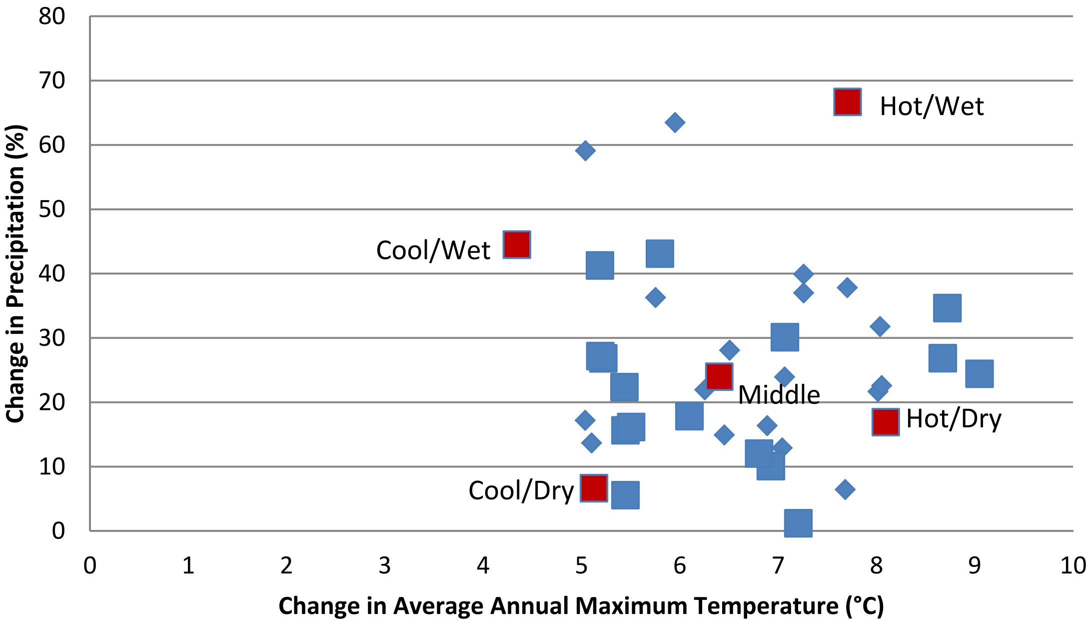
[2] NOAA Climate Division, web site: http://glisa.umich.edu/resources/great-lekes-climate-divisions. See Figure 2.1

[3] Note: The extremes analysis was based on those climate models that generated daily precipitation output for CMIP5.

Figure 3.1 Change in Temperature and Precipitation by Climate Model



These climate division-specific models were used to generate average annual, seasonal, and extreme event projections for the following scenarios:

Medium Emissions Scenario	High-Emissions Scenario
Hot/Dry model for 2050 and 2100	Hot/Dry model for 2050 and 2100
Hot/Wet model for 2050 and 2100	Hot/Wet model for 2050 and 2100
Cool/Dry model for 2050 and 2100	Cool/Dry model for 2050 and 2100
Cool/Wet model for 2050 and 2100	Cool/Wet model for 2050 and 2100
Middle model for 2050 and 2100	Middle model for 2050 and 2100

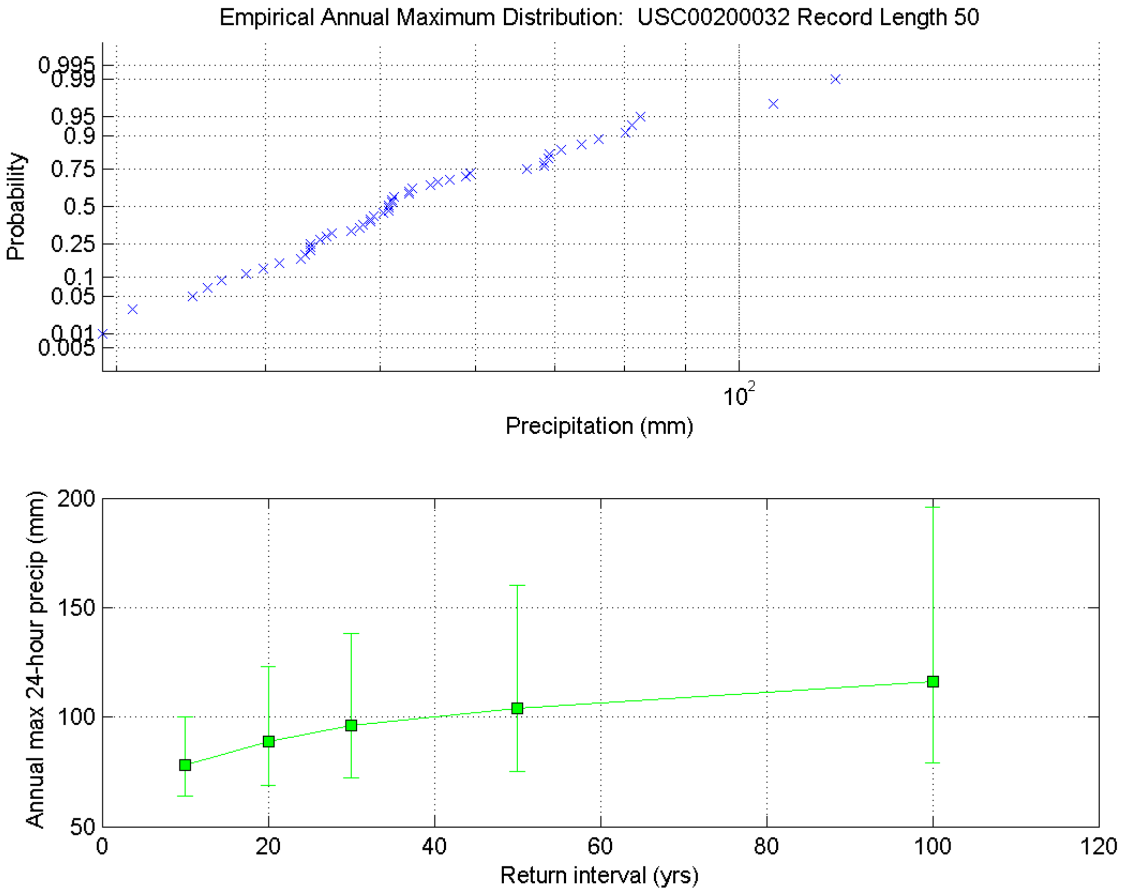
3.3.1 Extreme Projections

The extreme event projections include projections of temperature- and precipitation-based stressors. Temperature stressors include the number of days exceeding 95°F ("hot days"), the number of days below 32F ("cold days"), and the number of days with the maximum temperature above 32°F and the minimum below 32°F ("frost days"). Precipitation-based stressors include the historical 30-, 50-, and 100-year 24-hour precipitation events.

The historical temperature stressors were derived by summing the number of days meeting the criteria for each variable (hot, cold, and frost days) at each station and calculating the annual average over the 1981 to 2010 period. Projections for future conditions were derived by applying estimated monthly increases in temperature (deltas) from the climate model scenario at the location of each climate station to each day of the respective month in the observed daily data at each climate station. For example, the delta value at a specific climate station for January 2050 was added to each January day for each year (1981 to 2010). The average annual number of days exceeding the threshold for each variable was then calculated in the same manner as the historical temperature stressors.

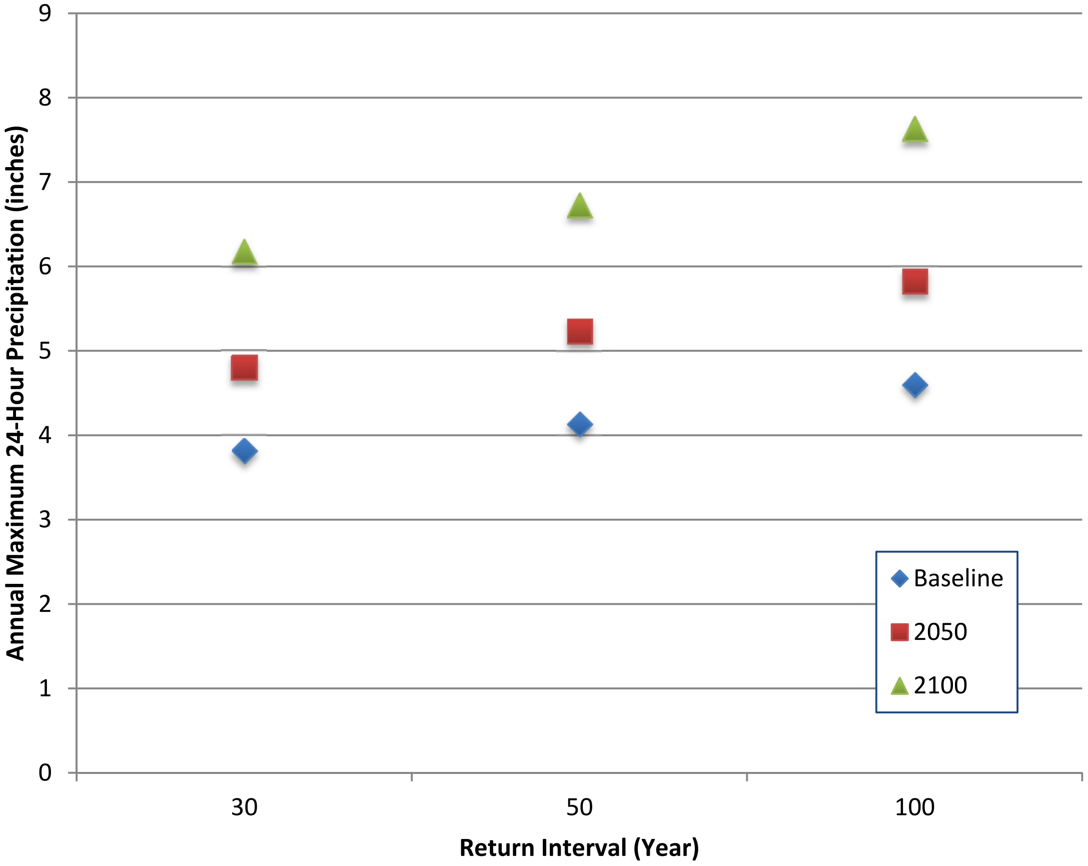
Extreme precipitation events for each climate station were derived by fitting a generalized extreme value (GEV) curve to the observed annual maximum-time series. Using the GEV fits to the observed data, the 24-hour maximum precipitation expected for three return intervals: 30, 50, and 100 years was estimated. Figure 3.2 shows an example of a GEV plot for an individual station.

Figure 3.2 Generalized Extreme Value Curve for a Select Station



Future GEV curves were generated for each station using spatially explicit scalars indicating the changes in magnitude of extreme precipitation events under each climate model and scenario. As with the climate model output for average conditions, extreme event scalars from individual models indicate the percentage change in a variable that has been normalized to increase with respect to global mean temperature. The scalars differ within each model from grid cell to grid cell and by the specific return period of interest. The resulting scalars for extreme precipitation events were applied to the baseline peak magnitudes of annual 24-hour rainfall events with the same return intervals. Figure 3.3 shows the return intervals under baseline and future projections (2050 and 2100) under the high-emissions scenario.

Figure 3.3 Change in Extreme Precipitation Return Intervals
High Emissions Scenario



The full range of outputs from these models will be included in the Final Report. Highlights from the data analysis are included in Section 4.0 of this Technical Report.

3.4 Downscaling

As climate models are designed to represent climate change processes at the global scale, the native resolution of the cells is often too coarse for use in regional impact analyses. In particular, this can make it difficult for the models to simulate lake effect precipitation. The CMIP3 data corresponding to the 4th Assessment (IPCC, 2007) had climate model horizontal resolution with cells of roughly 200 to 300 kilometers across. In the IPCC's latest Assessment, the horizontal CMIP5 model resolutions have improved to around 100 to 200 kilometers. Therefore, in both of these cases, the scale of climate model output is too coarse to use directly in the estimation of regional or local climate-related impacts to transportation. Therefore, this analysis utilized a set of climate data that has been rescaled using the Bias Correction Spatial Disaggregation (BCSD) technique to increase the resolution of the projections. In very general terms, BCSD uses statistical relationships between the climate model and aspects of the regional climate from observational data (e.g., temperature, precipitation) to refine (i.e., reduce the spatial scale) and adjust (i.e., bias correct) output to a particular region.

Additionally, that the data utilizes pattern scaling, which assumes that changes in regional climate for individual models follow a pattern relative to increases in global mean temperature (e.g., the degree that a region may get drier or wetter can be scaled to a change in global mean temperature). A scalar is derived from climate model output and is the percentage change in a variable normalized to increase in global mean temperature on a cell-by-cell basis. This analysis uses BCSD/scalar output that are calculated by CLIMSystems, Ltd, and are part of the SimCLIM software package (Warrick, 2009). The output of the data, at a resolution of 800 meters, is directly compatible with the PRISM baseline data and is generated at a resolution compatible with regional impacts analysis.

3.5 Qualitative Analysis

A literature review was conducted to compile information on trends and projections of the effects of climate change on Great Lakes water levels and wildland fire. The available literature on fire is limited in Michigan, so this research focused on more general drivers and trends.

3.5.1 Climate and Lake Levels

Climate has a dominant influence on water levels in the Great Lakes. Meteorological variables, including precipitation, temperature, wind, solar radiation, and humidity are important drivers of lake levels (Lenters et al., 2013). Precipitation directly influences lake levels by adding water to the watershed. Warmer air temperatures increase water temperatures, and thus increase evaporation from the lakes and evapotranspiration from the land, which reduces runoff into the lakes (Hayhoe et al., 2010). Higher winds and solar radiation increase evaporation, while a higher specific humidity reduces it.

The water balance in the Great Lakes varies both seasonally and on an interannual basis (Lenters et al., 2013). Seasonally, the highest precipitation tends to occur in the summer months, whereas the highest rates of evaporation – driven by a large temperature differential among the warmer water and cold air, low-relative humidity, and high-wind speeds – occurs between November and March (Lenters, 2004). Approximately 70 percent to 90 percent of the annual evaporation from Lake Superior occurs in these winter months (Blanken et al., 2011).

A further complicating factor in the water budget is the role of ice cover. Annual ice cover is highly variable, but records suggest that it is decreasing. The annual maximum ice coverage in recent years, which averaged 43 percent from 2003 to 2013, is lower than the 1962 to 2013 average of 52 percent (Pryor et al., 2014). Despite these decreases, ice cover varies dramatically from year-to-year. For example, in the unusually cold winter of 2014, the maximum extent of ice cover was 92 percent (NOAA, 2014). However, in 2012, the maximum ice coverage was only 13 percent, one of the lowest years on record (NOAA, 2014).

These changes in ice coverage influence the Great Lakes water budget and contribute to interannual variability. Reduced ice coverage can result in further increases in water temperatures and evaporation (Austin and Coleman, 2007). For example, in 2008 to 2009, a high-ice year, the evaporation rate from Lake Superior in February and March was much lower than in 2009 to 2010, a low-ice year (Lenters et al., 2013). Years with higher fall air temperatures have higher evaporation rates, which cause the water to cool more rapidly. This rapid cooling drives high-ice-cover winters, which are usually followed by cooler summer water temperatures and lower evaporation rates, in turn driving low-ice-cover winters (Van Cleave, 2012; Spence et al., 2013).

The Great Lakes currently experience several types of changes in water levels (IUGLSB, 2012). On an hourly to daily timescale, short-term fluctuations in water levels are caused by winds and changes in barometric pressure. On a seasonal basis, snowmelt and spring rainfall cause higher water levels in the spring and early summer. Finally, long-term fluctuations occur based on low or high-water supply conditions driven by climate patterns. Lakes Superior, Michigan, Huron, and Erie have experienced lower-than-average annual water levels in recent years (Gronewold et al., 2013).

3.5.2 Wildfire

Between 2000 and 2013, the Michigan Department of Natural Resources (MDNR) responded to between 199 and 613 fires each year (personal communication, Paul Kollmeyer, Resource Protection Section Manager, MDNR Forest Resources Division, July 25, 2014).[4] Over this time period, fires burned an average of 5,896 acres per year. However, the acreage burned varies significantly from year-to-year; the smallest burned acreage was in 2013, when only 740 acres burned, and the largest burned acreage was in 2012, when 23,814 acres burned (Figure 3.4).

Lightning currently plays a relatively small role in starting Michigan fires. Between 2000 and 2013, MDNR reported that lightning ignited an average of just 7 percent of Michigan fires per year, compared to an average of 10 percent of other U.S. fires (Price and Rind, 1994). However,

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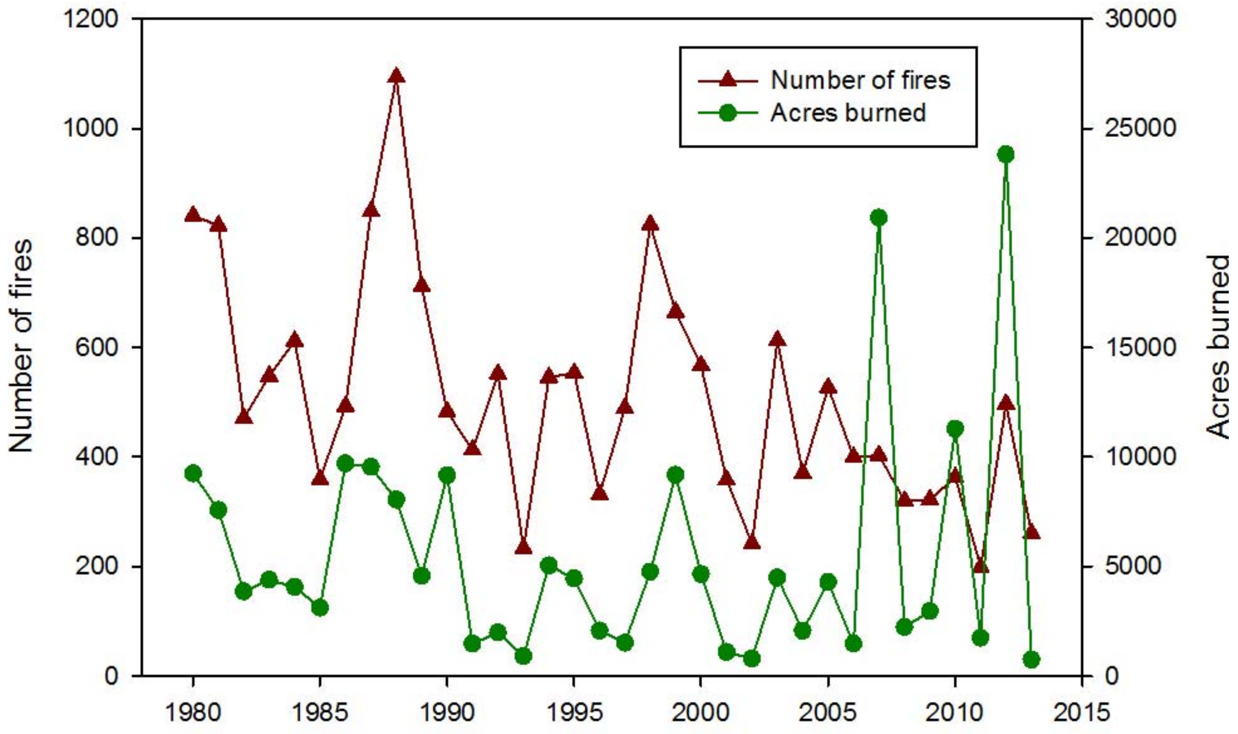
[4] Other Federal and local agencies also respond to fires in Michigan; on average in the past 10 years, MDNR was responsible for managing 70 percent of the fires and 78 percent of the acreage burned in Michigan (National Interagency Fire Center, 2014). Only the MDNR numbers are reported here because detailed records were maintained.

lightning-ignited fires in Michigan can be significant in terms of the area burned; for example, the 2012 Duck Lake fire, which lightning started, burned 21,114 acres, or 89 percent of the total burned acreage, which MDNR reported that year (MDNR, 2012).

In Michigan, the fire season extends from spring through fall (Michigan State University, 2014). Michigan's busiest fire season is in the spring, when dead leaves and grass from the previous season provide fuel and windy, dry days create an environment that encourages fires to ignite and spread (MDNR, 2014; Michigan State University, 2014).

The number of fires that MDNR fights has decreased in recent years because other agencies now manage a greater number of small fires.

Figure 3.4 MDNR fire statistics from 1980 to 2013



Source: Personal communication, Paul Kollmeyer, Resource Protection Section Manager, MDNR Forest Resources Division, July 25, 2014.

Extensive research has demonstrated that climate and weather, fuels, and ignition agents are key controlling factors for forest fires (Flannigan et al., 2009; Price and Rind, 1994). Increases in air temperature are expected to influence fire in several ways, including increasing the occurrence of lightning (Price and Rind, 1994), fuel quantity and condition (Flannigan et al., 2009), and the length of the fire season (Westerling et al., 2006). Research on historical fires in the Upper Peninsula of Michigan indicates that larger fires were associated with drier climactic conditions and droughts (Drobyshev et al., 2012). An increase in precipitation is unlikely to mitigate the effect of increasing air temperatures because warmer air increases evaporation and can hold more moisture (Flannigan and Harrington, 1988; Flannigan and Van Wagner, 1991; Flannigan et al., 2005). Parisien et al. (2011) showed that the area a fire burns tends to increase with higher temperatures, even when precipitation is high. The timing of precipitation also is important. More precipitation in the previous season actually increases fuels because it increases net primary productivity (Westerling et al., 2006; Swetnam and Betancourt, 1998; Meyn et al., 2007); primary productivity is an important influence on the distribution of fire (Flannigan et al., 2009; Krawchuck et al., 2009).

4.0 PRELIMINARY CLIMATE ANALYSIS FINDINGS

4.1 Precipitation

The average annual precipitation in Michigan has been increasing in recent years, on the order of 0.45 inches per decade (based on data from 1960 to 2010; National Climatic Data Center, 2014). The increase has been similar in both summer (June, July, and August), 0.12 inches per decade, and winter (December, January, and February), 0.13 inches per decade.

The vast majority of models project an increase in annual precipitation in Michigan, although a small number project virtually no change, or even a slight decrease. Although there is considerable variability in the projected changes in precipitation between the five selected models for each region, all project increased precipitation in Michigan (Figure 4.1).[5] On a percentage basis, the projected average annual change is similar across all three regions. Similarly, there is considerable variability in the projections of summer and winter precipitation (Figure 4.2 and Figure 4.3). However, the five selected models on average project lower increases in summer precipitation than the annual values, or even slight decreases. The projections of increases in winter precipitation are on average higher than annual values, although some models project a decrease in winter precipitation as well.

Figure 4.1 presents the regional average projected percentage change in average annual precipitation for the medium and high-emissions scenarios in 2050 and 2100 compared to the 1995 baseline. The triangle represents the average change from all five models, and the horizontal bars represent the maximum and minimum values from the 5 models.

Figures 4.2 and 4.3 show the regional average projected percentage change in average summer (June, July, and August) and winter (December, January, February) precipitation for the medium- and high-emissions scenarios in 2050 and 2100, compared to the 1995 baseline.

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[5] Note that the models selected illustrate a range of temperature and precipitation; however, none of the models selected for the summary showed a decrease in precipitation.

Figure 4.1 Percent Change in Average Precipitation by Scenario, Region, and Year

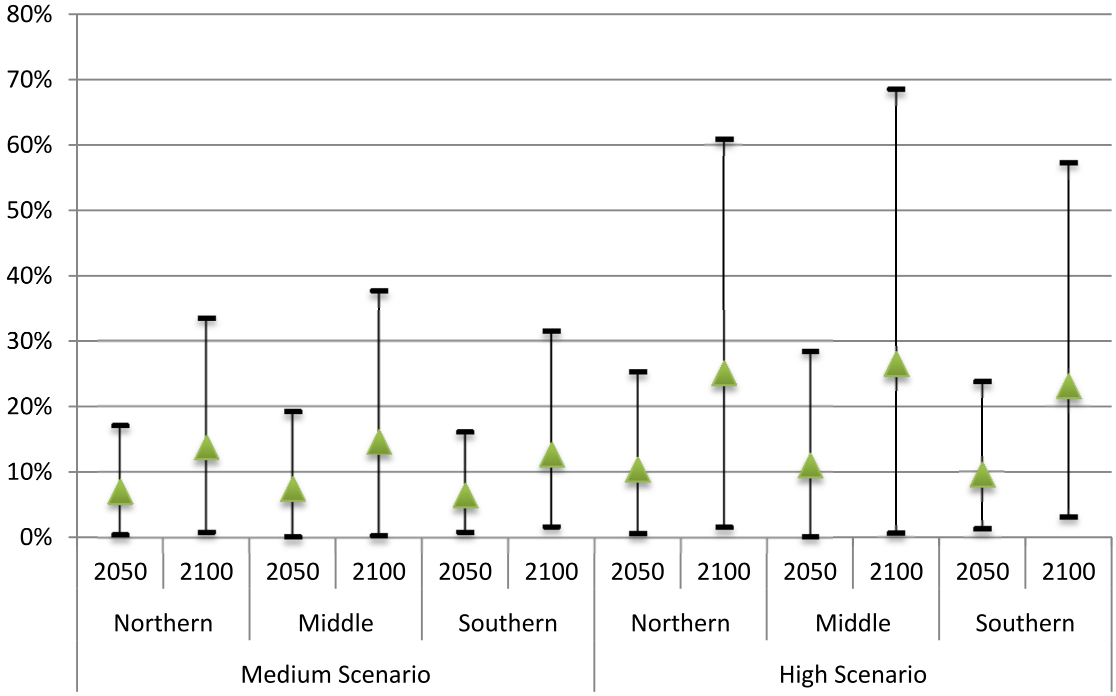


Figure 4.2 Percent Change in Summer Precipitation by Scenario, Region, and Year

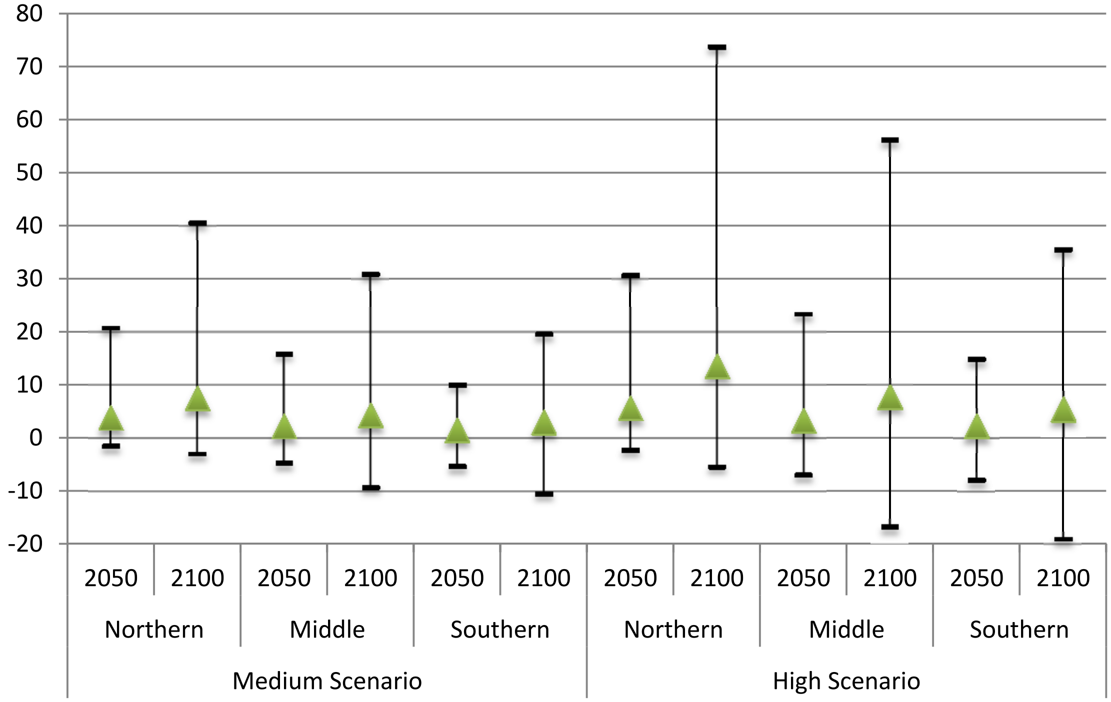
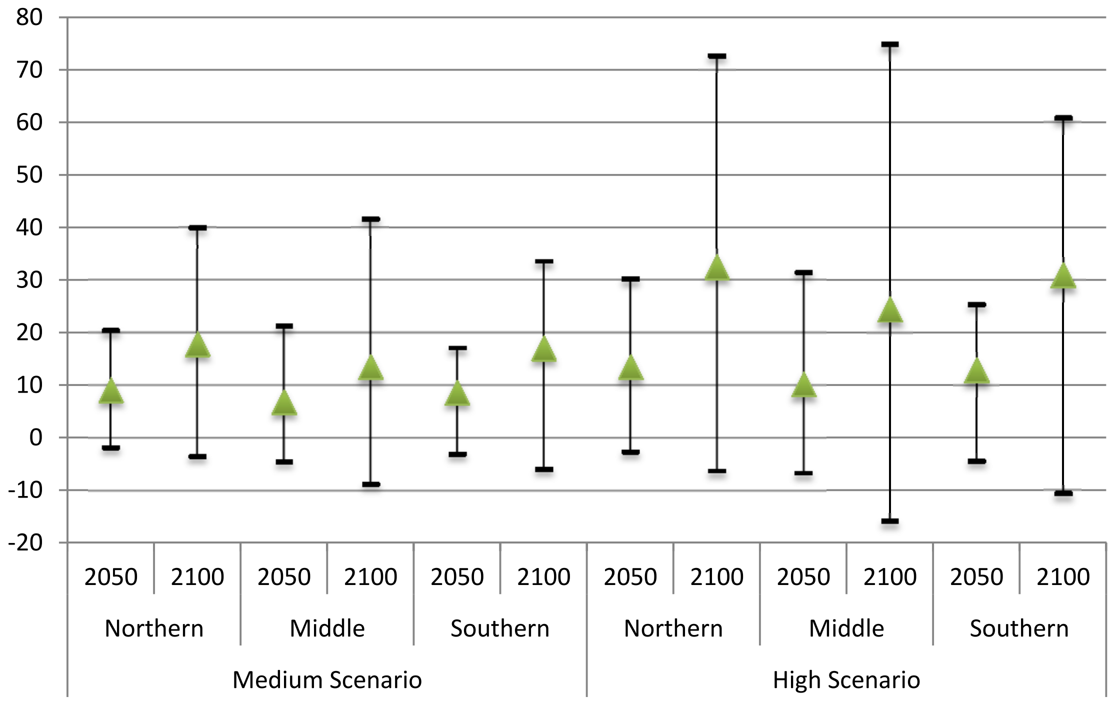


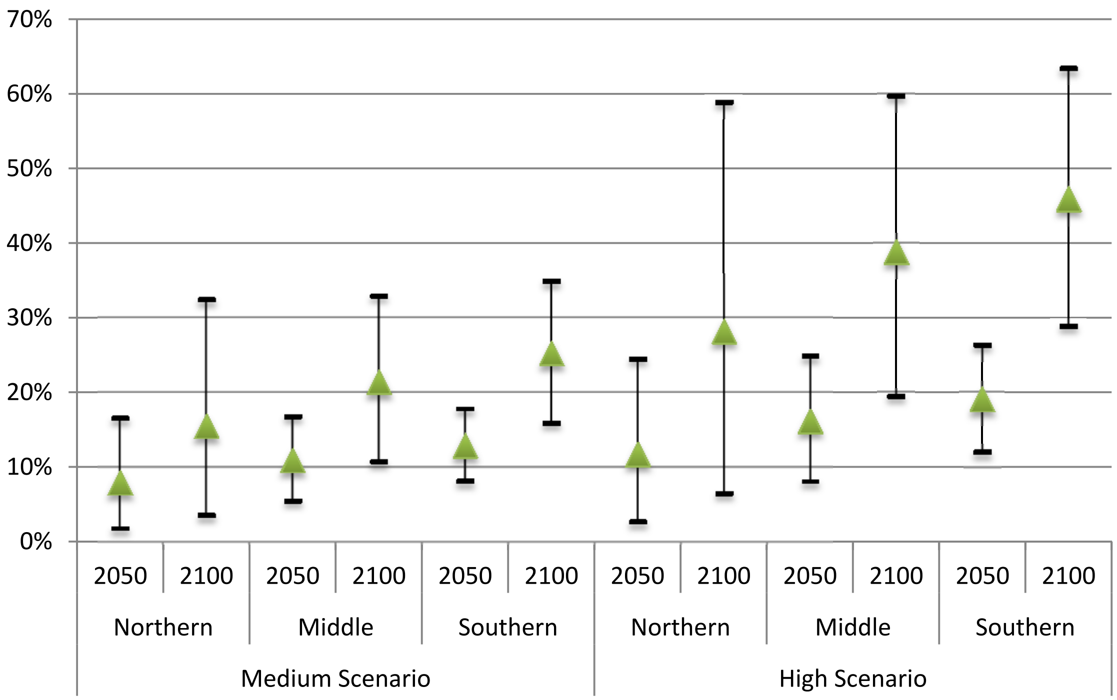
Figure 4.3 Percent Change in Winter Precipitation by Scenario, Region, and Year



4.1.1 Extreme Precipitation Events

The models project an increase in the average magnitude of 100-year, annual extreme 24-hour precipitation events over the next century, with minimal differences between the three regions (Figure 4.4). Note that the higher emissions scenario shows much more variability in the projections for 2100 (a range of 50 percent) compared to the medium emissions scenario (a range of 20 to 25 percent). Thus, while there is a clear expectation for increased precipitation, the magnitude of that change is uncertain.

Figure 4.4 Change in Hundred-Year Precipitation Amount by Scenario, Region, and Year



4.2 Temperature

The average, minimum, and maximum annual temperatures in Michigan have increased from 1960 to 2010, on the order of 0.5°F per decade (National Climatic Data Center, 2014). Average, minimum, and maximum winter temperatures have increased at a greater rate over this 50-year period than summer temperatures.

The model projections suggest that the annual average, minimum, and maximum temperatures will continue to increase under both emission scenarios (Figure 4.5, Figure 4.6, and Figure 4.7). The increase in temperature is projected to be similar across the three regions of the State. Under the medium emission scenario, the average increase in annual average projected by the models is approximately 3.1°F (1.7°C) in each region by 2050 and approximately 6.1°F (3.4°C) in each region by 2100. Under the high-emission scenario, the increase in annual average projected by the models is approximately 4.5°F (2.5°C) in each region by 2050 and approximately 11.0°F (6.1°C) in each region by 2100. The changes in annual minimum temperature and maximum temperature are projected to be similar to the change in average temperature.

Figure 4.5 Expected Change in Average Temperature by Scenario, Region, and Year

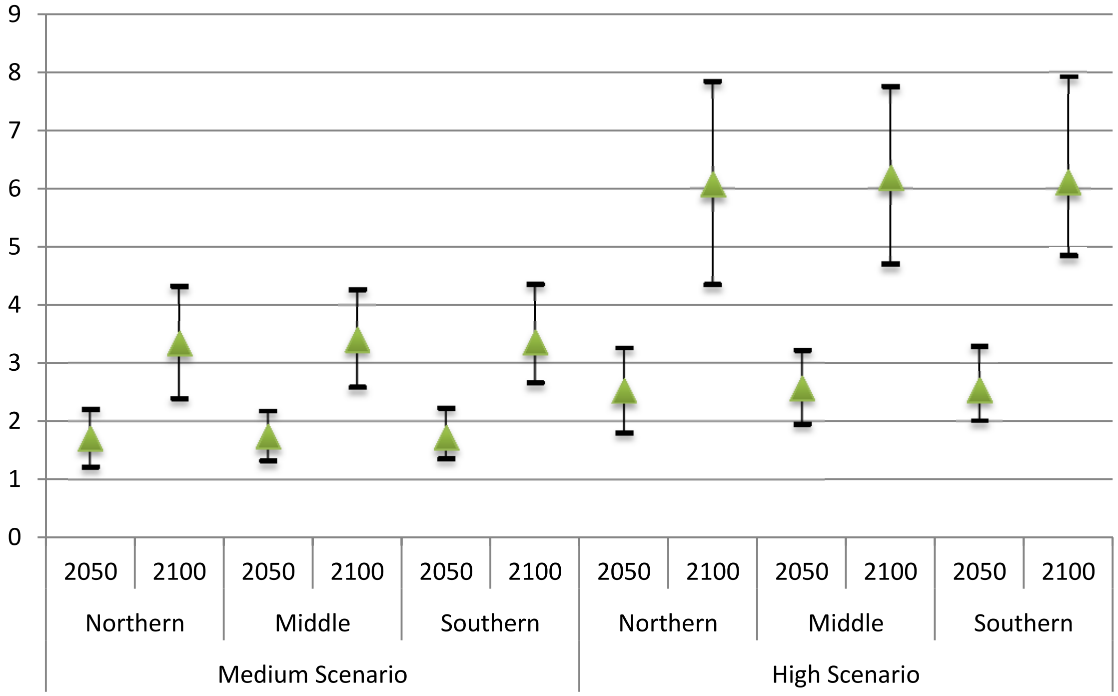


Figure 4.6 Expected Change in Minimum Temperature by Scenario, Region, and Year

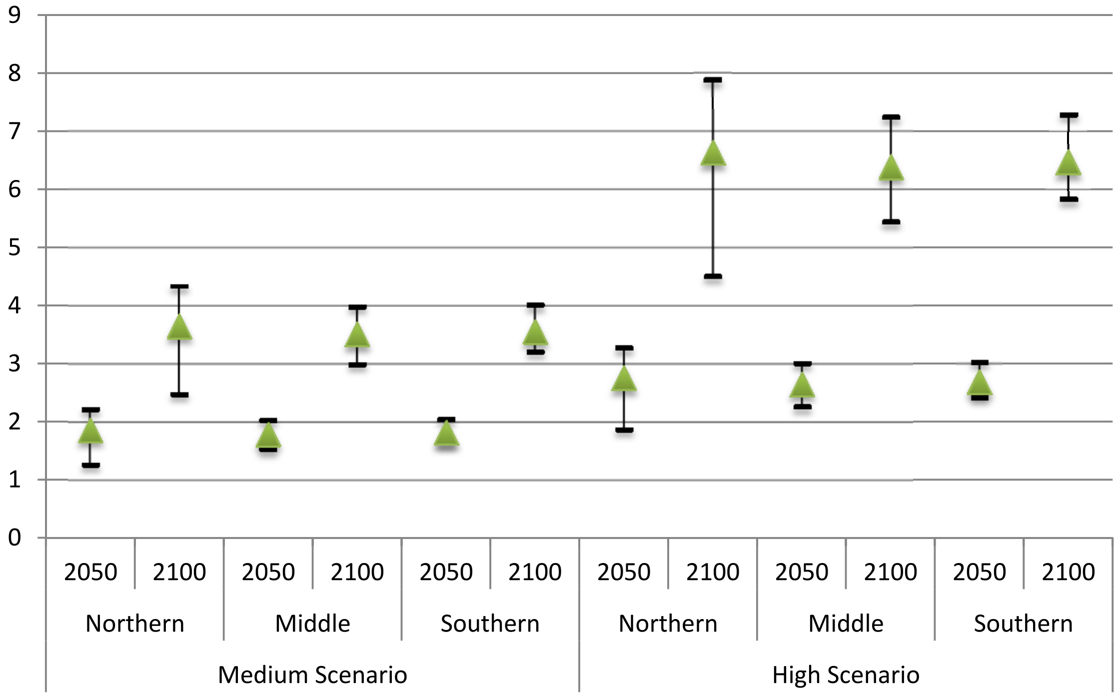
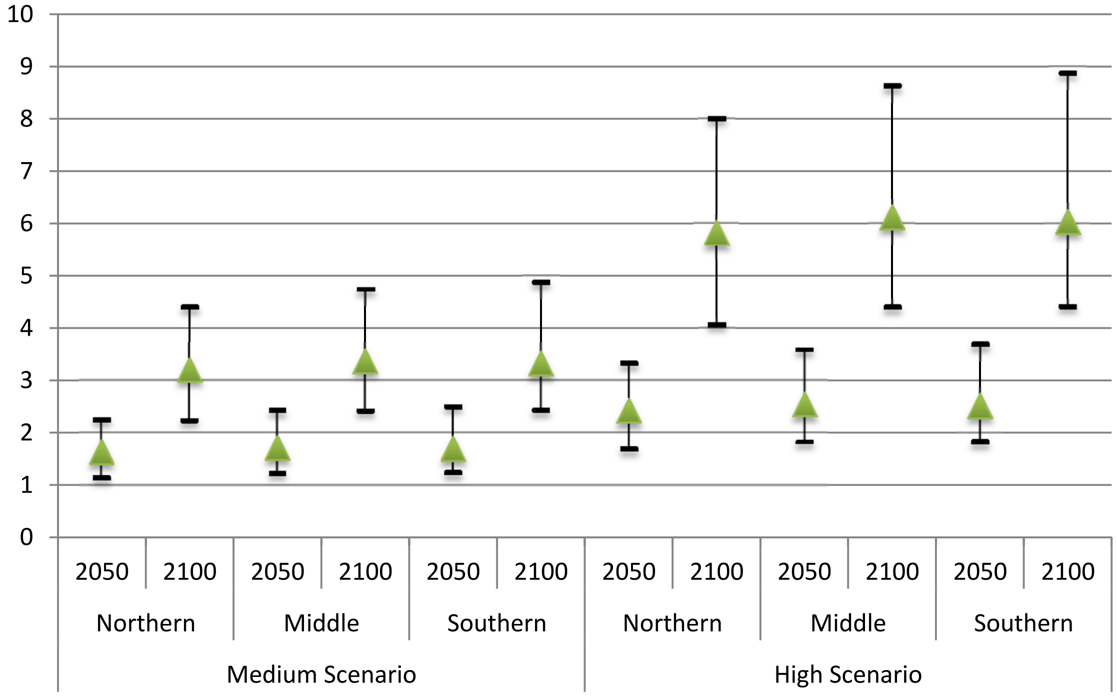


Figure 4.7 Expected Change in Maximum Temperature by Scenario, Region, and Year



Average, maximum, and minimum summer temperatures are projected to increase in a similar manner as annual average temperatures, as are maximum winter temperatures (data not shown). However, on average, the models project greater increases in mean and minimum temperatures in the winter than the annual averages (Figure 4.8, and Figure 4.9), which is consistent with the past trends discussed above.

Figure 4.8 Winter Average Temperature

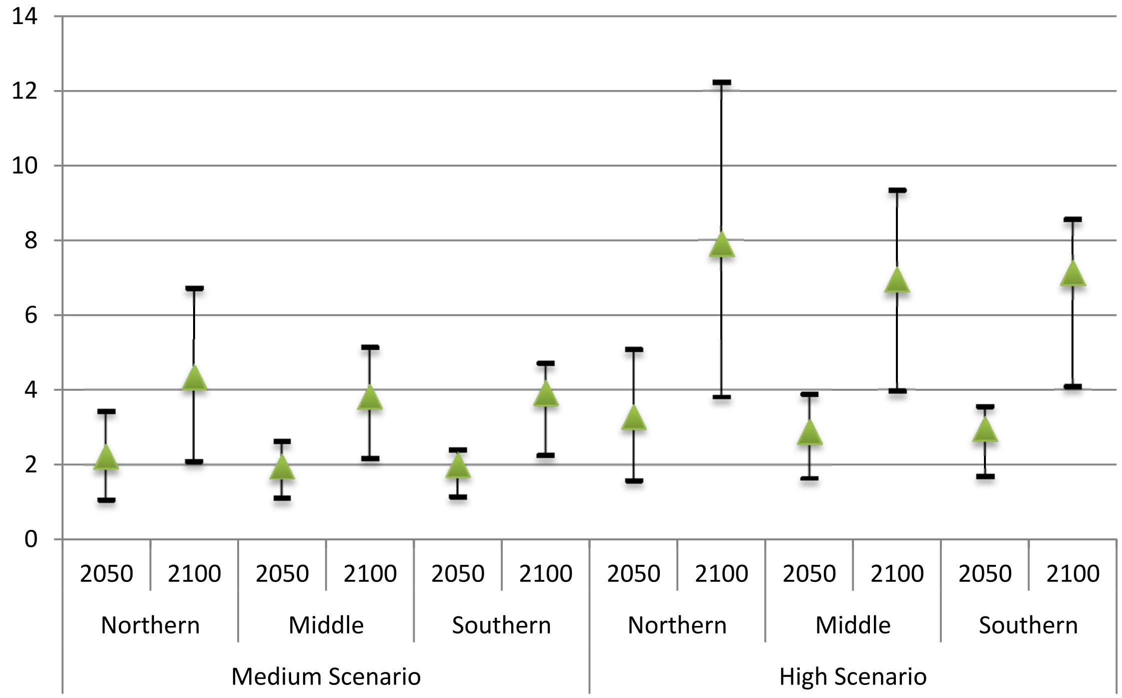
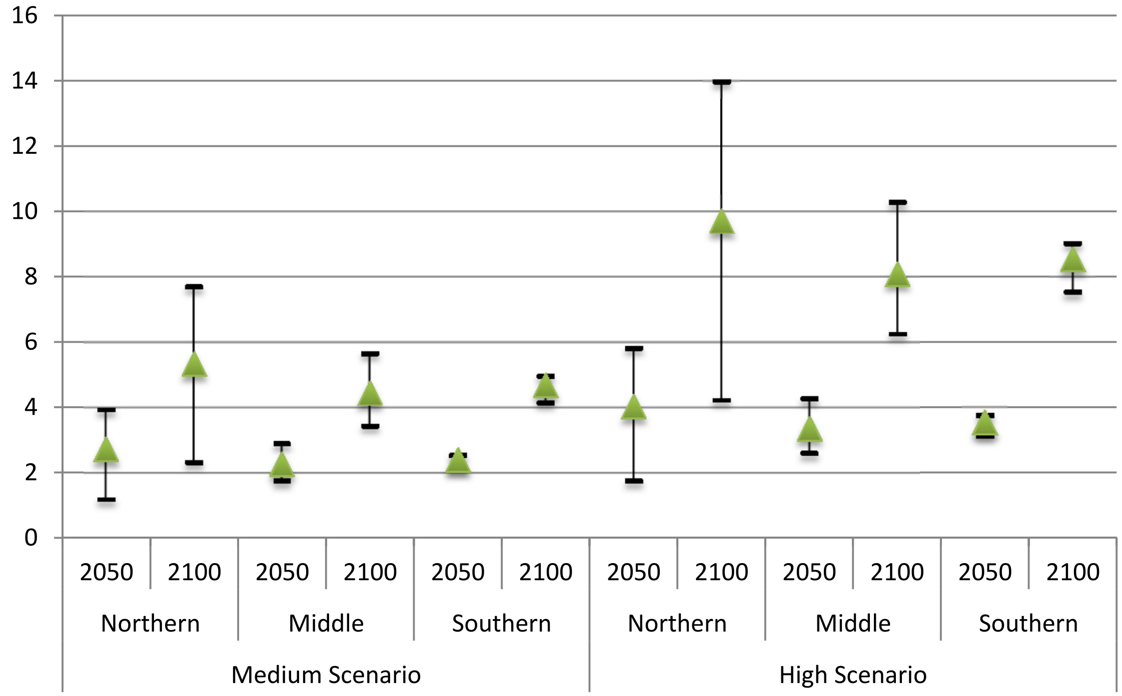


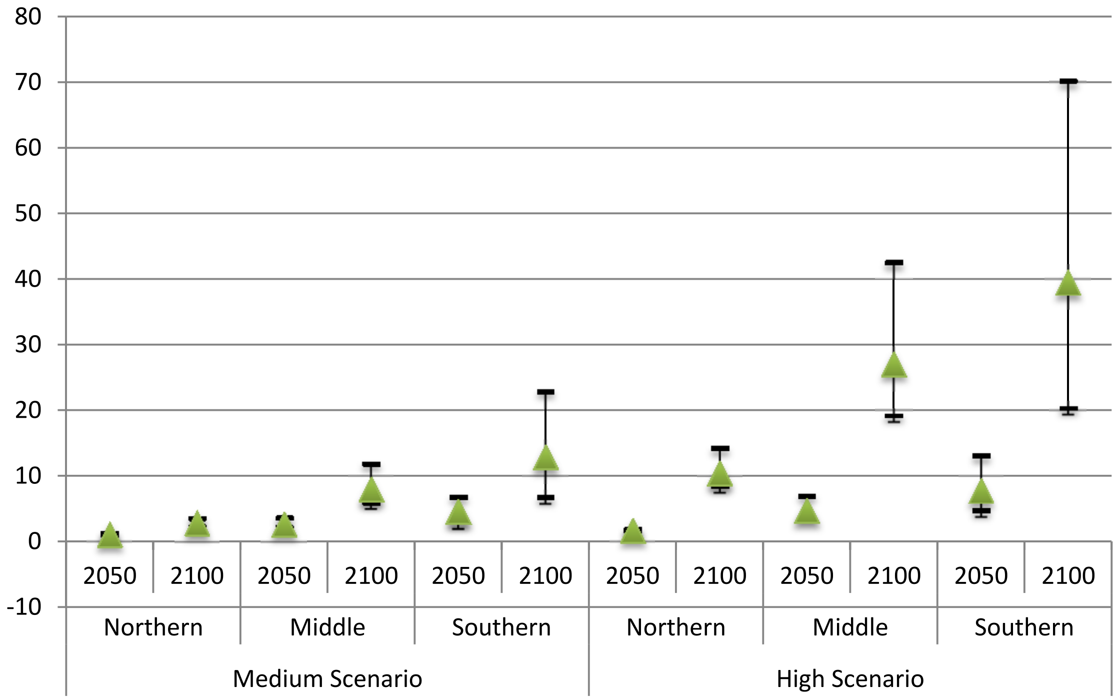
Figure 4.9 Winter Minimum Temperature



4.2.1 Hot Days

Currently there are very few days that exceed 95°F ("hot days") in Michigan. For the baseline period, there was less than one hot day per year on average in each of the three regions. Hot days are projected to increase across Michigan under both emission scenarios (Figure 4.10). The greatest increases are projected for the Southern region, followed by the Middle region.

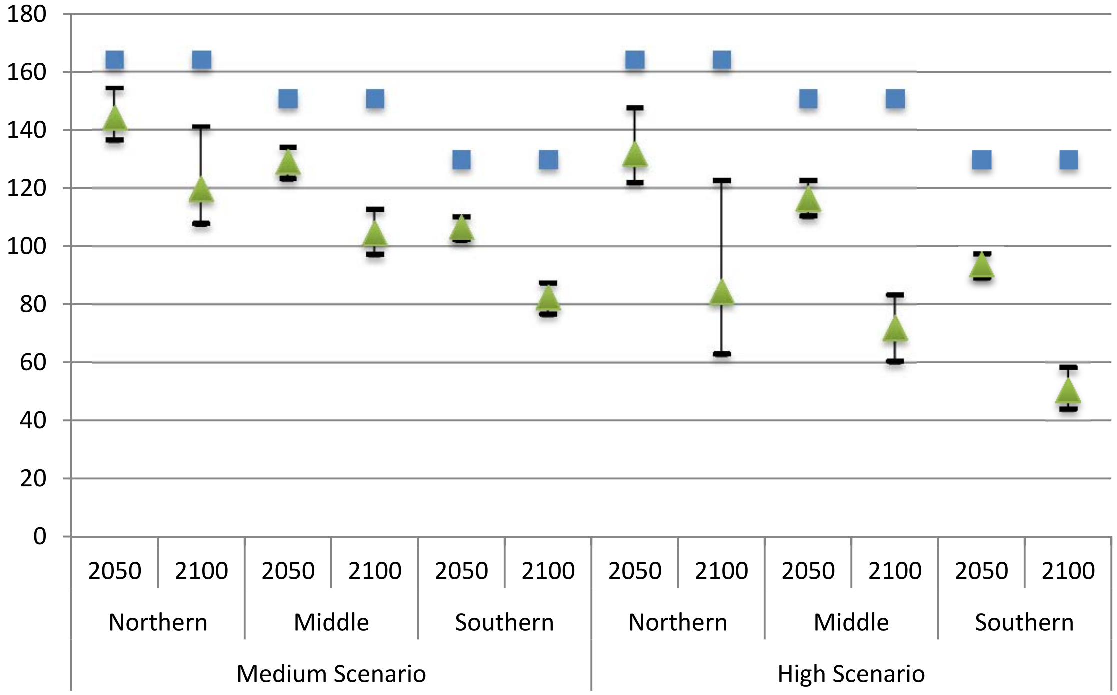
Figure 4.10 Change in Hot Days (over 95 °F) by Scenario, Region, and Year



4.2.2 Days Below Freezing (Cold Days)

The northern region currently experiences an average of 165 days below freezing per year, the middle region 152 days, and the southern region 132 days. All of the climate models project that the number of cold days will decrease under both emission scenarios, both by 2050 and by 2100. Following the current geographic pattern, the southern region is expected to experience the fewest number of cold days and the northern region the highest number of cold days. By 2100, the southern region could experience approximately 52 cold days per year on average (high-emissions scenario; average of model results).

Figure 4.11 Expected Number of Days Below Freezing by Scenario, Region, and Year

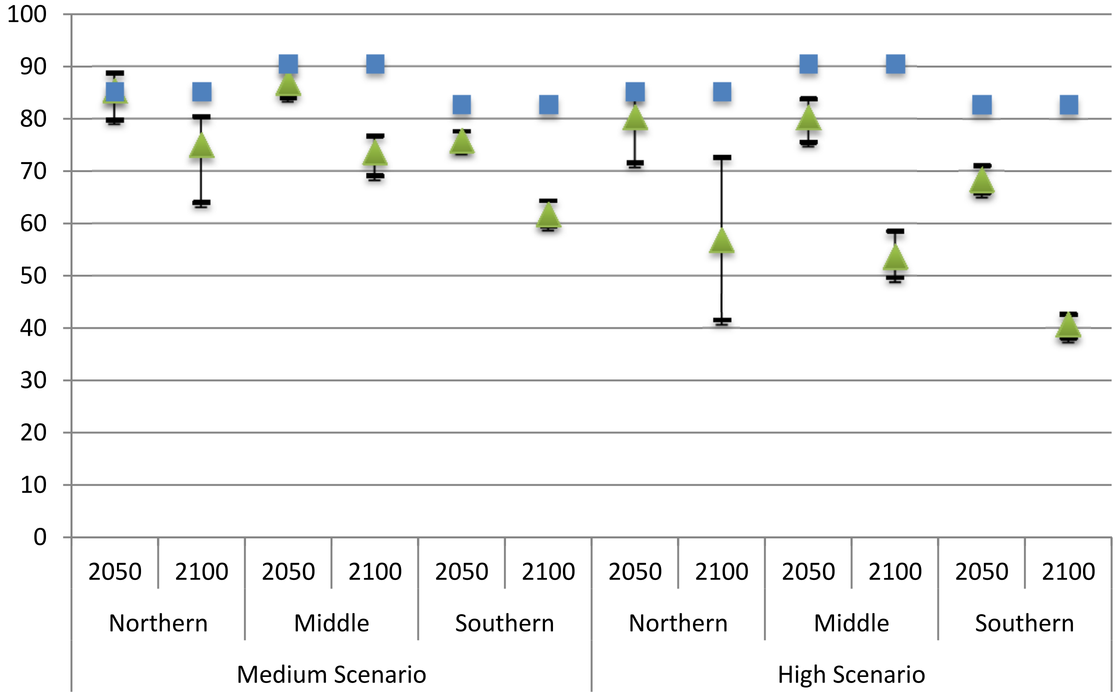


Note: Blue boxes represent the current average regional number of frost days.

4.2.3 Frost Days

Currently, the northern, middle, and southern regions of Michigan experience an average of 86, 92, and 84 days, respectively, with the maximum temperature above 32°F and the minimum below 32°F ("frost days"). This analysis was conducted to approximate the change in freeze-thaw conditions in Michigan. Projections from both scenarios were considered suggesting that this same pattern holds in 2050, with the middle region experiencing slightly more frost days than the northern or southern regions. However, by 2100, both scenarios suggest that the greatest number of frost days could occur in the northern region. By 2100, the southern region could experience approximately 42 frost days per year on average (high-emissions scenario; average of model results).

Figure 4.12 Number of Frost Days by Scenario, Region, and Year



Note: Blue boxes represent the current average regional number of frost days.

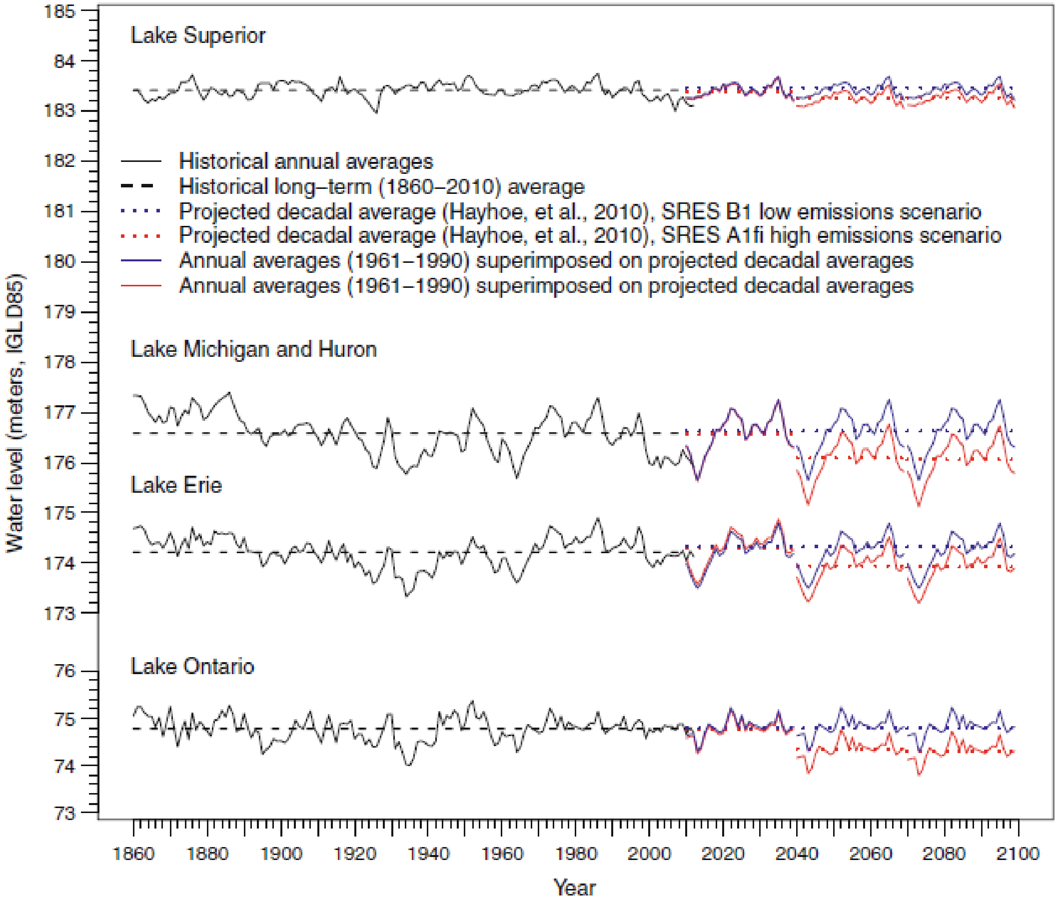
4.3 Climate Change and Lake Levels

Projections of future Great Lakes water levels represent an area of evolving research and uncertain findings: even whether average lake levels will rise or fall is uncertain. The uncertainty is largely because of the difficulty associated with measuring and estimating evaporation in such a large and complex system (Lenters et al., 2013).

Hayhoe et al. (2010) considered the possible effects of a range of greenhouse gas (GHG) emission scenarios on average Lake Michigan water levels. The authors found that the level of Lake Michigan may decrease by more than 0.5 meters by the end of the 21st century under the higher A1FI GHG emission scenario (Hayhoe et al., 2010). However, in the shorter term and under the lower B1 GHG emission scenario, the authors anticipated little net change. The authors also noted that variations on the order of several feet are likely to continue to occur on decadal timescales (Figure 4.13). However, newer evaluations project only a slight decrease or even a small rise in average lake levels (Angel and Kunkel, 2010; MacKay and Seglenieks, 2011; Gronewold et al., 2013). Gronewold et al. (2013) concluded that earlier models likely exaggerated the feasible losses from evapotranspiration.

Finally, the IUGLSB (2012) reviewed several of these modeling efforts and concluded that changes in lake levels over the next 30 years are likely to remain within the historical range and climate change influences will likely be masked by natural variability – but that climate change could cause more extreme high- and low-water levels in Lakes Superior, Michigan, Huron, and Erie beyond the next 30 years. Thus, although the long-term average changes may be uncertain, the studies on future lake levels suggest a rise in the variability of lake levels.

Figure 4.13 Historic Annual Great Lakes Water Levels and Forecasts



Source: Gronewold et al., 2013, Figure 7b., from Hayhoe et al., 2010.

4.4 Wildfire

Modeling results suggest that climate change will result in more and larger fires; however, the magnitude of these changes is uncertain. Mills et al. (2014) developed projections of burned areas for the United States under an unconstrained emission scenario, with a total radiative forcing of 10 W/m^2 by 2100. To develop these projections, Mills et al. (2014) used the MC1 dynamic global vegetation model and three different models that project future climate (one global climate model and two pattern-scaled models).[6] Using data provided by the authors, future projections from each of the three models from 2001 to 2100 were compared to the output of the MC1 model from 1901 to 2000. The results from the global climate model, which was designed to incorporate and reflect variability, suggest that the number of large fire years and the average annual area burned could increase substantially in Michigan, particularly in the middle and southern regions. This is consistent with the nature of this particular model, which assumes hotter and wetter conditions, and therefore more vegetation growth. The two pattern-scaled models, which tend to smooth out variability, predictably projected smaller changes, or even decreases, in the number of fire years and the average annual area burned.

Although little research exists specific to Michigan, large-scale models and research on nearby areas provide some indication of the effects that climate change may have on Michigan fires. Podur and Wotton (2010) modeled fire frequency and area burned in Ontario, to the north of the Great Lakes, using two models and three emission scenarios (A2, A1b, and B1). Depending on the scenario and model used, their results suggest that the number of fires could increase by between 1 and 14 percent by 2040, and by between 8 and 89 percent by 2090; it is expected that the amount of land burned could increase by between 81 and 190 percent, and between 120 and 1,800 percent for the same time periods. These large increases in burned area are in part driven by assumptions about the number of fires that escape initial containment, which the authors defined as growing larger than 4 hectares (roughly 10 acres); these numbers may not be appropriate for Michigan. Research by Le Goff et al. (2009) for central Quebec may provide some insight into the timing of fires in Michigan, as impacted by climate change. The authors modeled fire risk in 2100 under the A2 scenario and found that overall, fire activity could increase slightly (by 7 percent) and that the peak fire risk could shift to later in the season, the August fire risk could more than double (increase by 110 percent), while the May risk could decrease slightly (by 20 percent).

Under warmer and drier conditions, similar to the extreme drought in May 2012 when the Duck Lake fire occurred (MDNR, 2013), lightning could become a more significant ignition source in Michigan. Price and Rind (1994) used a climate model to predict that changes in the hydrological cycle and thunderstorm activity associated with a doubling of carbon dioxide will increase the number of lightning-ignited fires. The authors suggest that lightning-ignited fires in the United States could increase by 44 percent by the end of the 21st century, while the associated area burned could increase by nearly 80 percent. However, the model that the authors used was not

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[6] Models used by Mills et al. (2014) were 1) the IGSM Community Atmospheric Model (CAM) framework (Monier et al. 2013); 2) the Model for Interdisciplinary Research on Climate (MIROC3.2-medres), which projects drying and a strong warming; and 3) the Community Climate System Model (CCSM3.0), which projects more moisture and less warming than MIROC. See Monier et al. (2014) for methodological details.

as accurate for the Midwest and Northeast regions of the United States as it was for the rest of the country, so uncertainty remains regarding the future role of lightning-ignited fires.

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